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MANUFACTURING TECHNOLOGY FOR HIGH VOLTAGE POWER SUPPLIES (HVPS)

Volume IV - Reference Information

Northrop Grumman Corporation
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600 Hicks Road
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13. ABSTRACT
This report is the culmination of a multi-year manufacturing technology program sponsored by the Electronics Division of Wright Laboratory Manufacturing Technology Directorate (WL/MTM). The program was jointly conducted by Northrop Grumman Electronics and Integration Division as the prime contractor and Hughes Aircraft Company Technology Support Division as the principal subcontractor. The thrust of this program was to improve the reliability of High Voltage Power Supplies (HVPS). This was accomplished by conducting a comprehensive evaluation of the materials, components and processes used to produce HVPS. To demonstrate the benefits of the program the lessons learned were incorporated into two existing HVPS, ALQ-135 and AMRAAM. Several of these upgraded high voltage assemblies were fabricated and tested to measure the benefits resulting from the changes.
The report is published in four volumes. The first volume is a summary of the technical activity and highlights of the program. The remaining three volumes provide the specific program and procedural details and reference information generated in performance of the effort. This report, Volume IV - Reference Information, contains specific construction details on Model Test Structures used throughout the program as well as test results obtained from the various material and component studies.

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High Voltage Power Supplies (HVPS), Traveling Wave Tube, High Voltage Materials Testing and Screening.

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DESIGN AND MANUFACTURING GUIDELINES FOR HIGH VOLTAGE POWER SUPPLIES

VOLUME 4

REFERENCE INFORMATION

Table Of Contents

GENERAL INTRODUCTION

The Guidelines contained here-in are presented in four volumes:

Volume 1, Design and Manufacturing Guidelines for High Voltage Power Supply, Program Summary.

Volume 2, Program Details, gives introductory and background information, the approach used, design/development considerations and general information for use by High Voltage Power Supply designers and manufacturers.

Volume 3, Procedural Details, contains procedures on how to perform the various component, material and process evaluations, and gives results obtained from the Northrop Grumman/ Hughes Aircraft Company efforts. The volume 3 procedures are basically stand alone documents and have been numbered as such. They can be referenced for specific areas of interest or treatment of problems; however, when reference is made to Model Test Structures, Volume 3 should be viewed for specific construction details.

Volume 4, Reference Information, contains specific construction details on Model Test Structures used throughout the program as well as test results obtained from the various material and component studies.

The information developed in these four volumes is the result of a joint Northrop Grumman Electronics Systems and Hughes Electro-Optical Systems effort initially begun in mid-1990. The initiative and primary funding for this effort was provided by Wright-Patterson AFB, Wright Labs ManTech Directorate, project manager M. Price. Supplemental funding from internal R & D funds was also provided by Northrop Grumman. General Research Corporation (J. Basine, K. Dunker) and consultant, W. Dunbar, served as contract monitors during the course of the program.

Note: Because the information presented is from research provided by multiple sources within each of the two contractors (as well as numerous third party sources), the writing styles, formatting and print emphasis vary somewhat. This should not detract from the content in any way.

1.0 Model Test Structures

The use of Model Test Structures (MTSs) to simulate actual hardware is an important technique to reduce labor and material cost when evaluating the performance of a High Voltage Power supply subassembly. The test structures can generally be designed, fabricated and tested for a fraction of the cost of actual hardware. Furthermore, an experimental matrix using a quantity of subassemblies (with controlled changes for example) would be prohibitive if actual hardware had to be used. A useful example of a model test structure used in the course of this program is given in Section 1.1, High Voltage Transformer Test Structure.
In some cases, a relatively simple test structure to measure characteristics of a material or component was devised. Examples are detailed in Sections 1.2 through 1.7.

1.1 High Voltage Transformer Test Structure(s)

Figure 1 shows a typical high voltage power transformer used by Northrop Grumman in airborne applications. This is a complex, relatively expensive structure that has evolved to meet the volume, weight, cooling and operating conditions of military aircraft. Simplifying it to make it useable as an evaluation tool led to the structure illustrated in Figure 2. The key winding, shielding and encapsulation elements are in place to obtain testable, representative comparisons. The test structure served to evaluate encapsulants, wire performance and fabrication techniques and was subjected to environmental testing in addition to electrical operating stresses. Appendix 4-1 gives specific construction details of the Transformer Test Structure (Section A) and a Test Vehicle Specification (Secton B) that is typical for a military transformer.

Figure 3 is a simplified test structure which was used to focus specifically on different wire types (temperature ratings) experimentally matrixed with various methods to strip the wire insulation where it mates to the terminals. This test structure refinement was invaluable in quickly proving that reliability of the wire-terminal connection is highly dependent on the stresses set up in the wire from stripping methods. Appendix 4-2 gives both fabrication and test details for this simplified test structure.

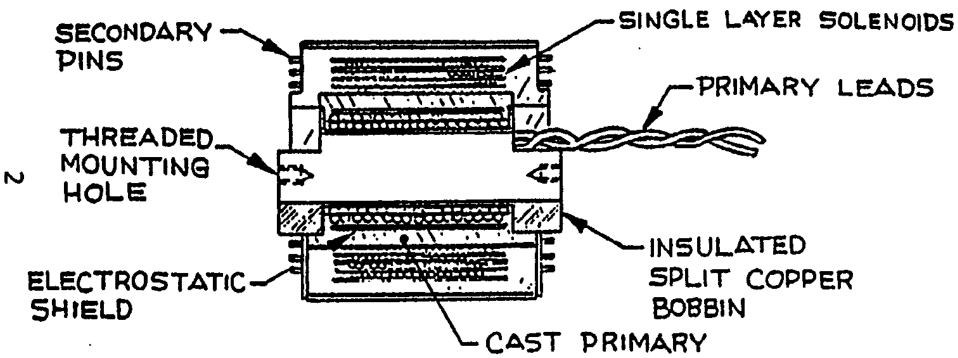


Figure 1

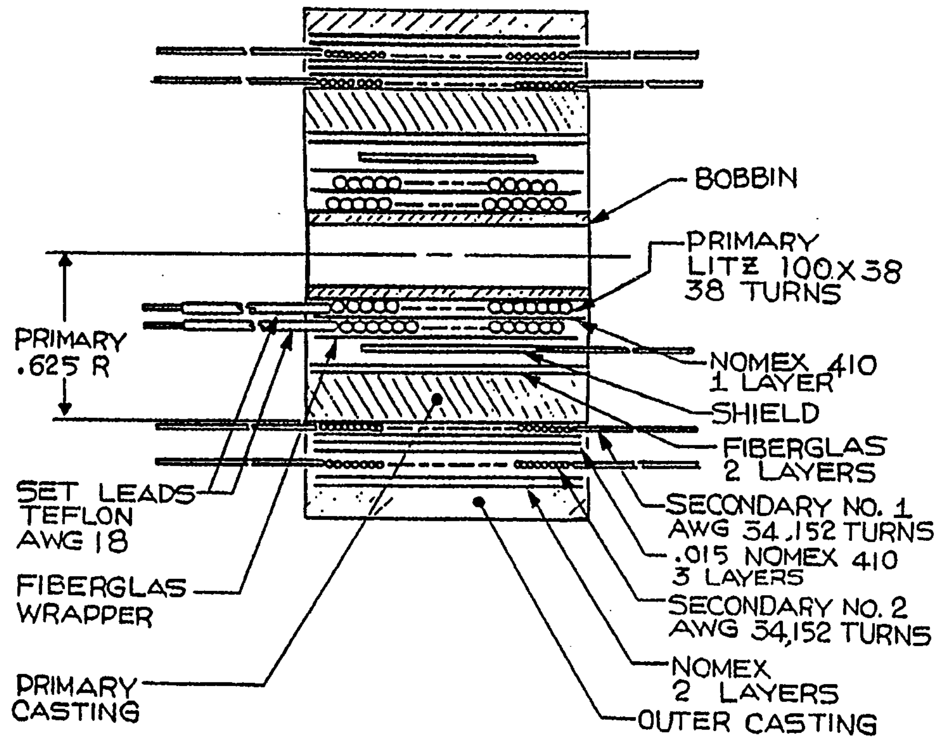
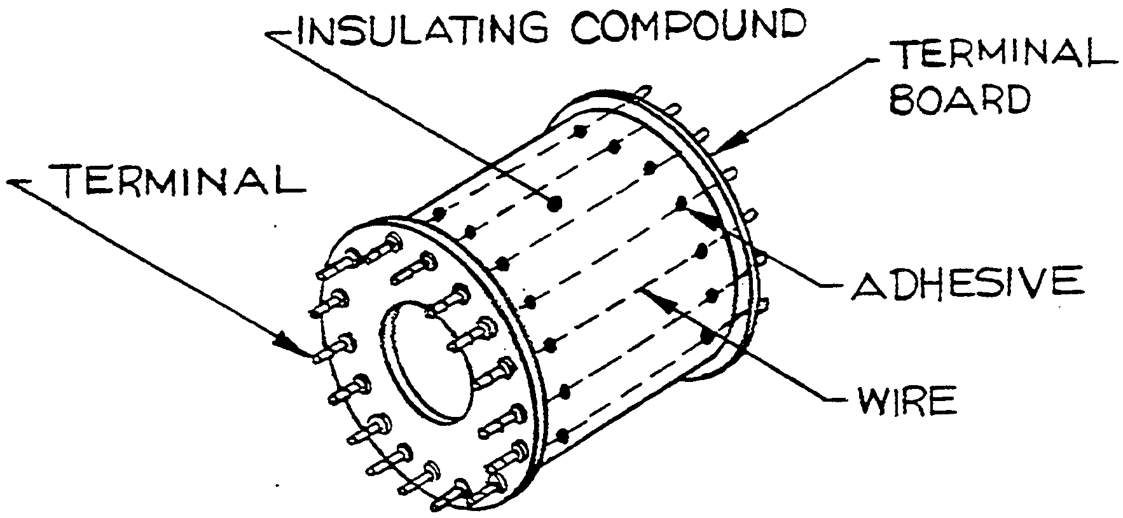
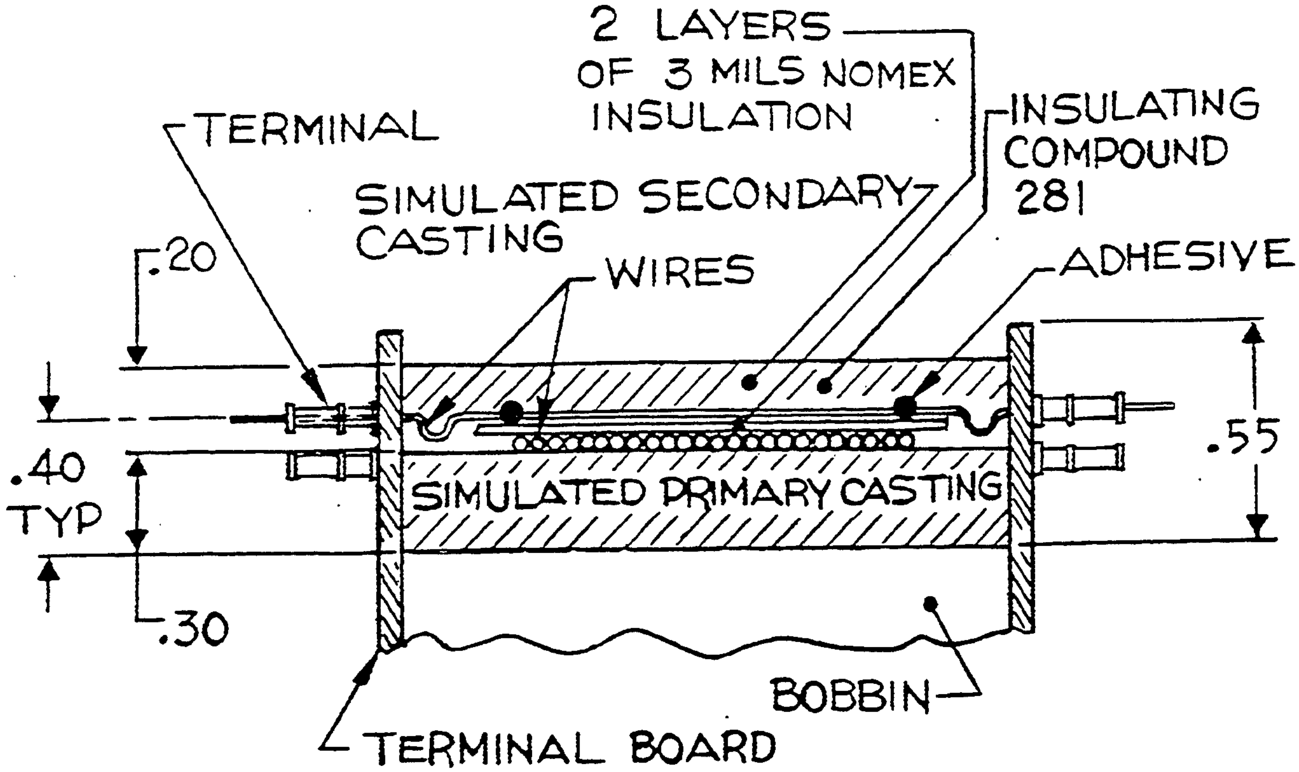


Figure 2



TEST FIXTURE



SECTION VIEW

FIGURE 3. CAST SECONDARY

1.2 Printed Wiring Board Test Structure

The capability of printed wiring boards to carry high voltage is of concern when space requirements preclude the use of more conventional wiring and harnessing. In small high voltage encapsulated assemblies, PWBs generally serve as interconnects and their performance and reliability should be assessed. Model Test Structures serve as a useful tool to:

- DETERMINE VIABILITY OF ETCHED CONDUCTORS (PWBs) AS HV INTERCONNECTS
- ASSESS NEED FOR RADIUSING ETCHED CONDUCTORS
- IDENTIFY ROLE OF ENCAPSULANT TYPE IN HV PERFORMANCE
- DETERMINE EFFECTS OF CONDUCTORS SPACING ON HV PERFORMANCE
- DETERMINE INFLUENCE OF OPPOSED GROUND PLANE (THRU LAMINATE) ON HV PERFORMANCE
- ESTABLISH EFFECTS OF THERMAL STRESSES ON HV PERFORMANCE

A test matrix to evaluate performance might consider variations in the test structure configuration (as illustrated in the figures that follow) as well as a variety of fabrication and test factors:

<u>DESIGN</u>

CONDUCTOR SPACING
RADII
LENGTH
THICKNESS
WIDTH

GROUND PLANE
- SUBSTRATE
- ENCAPSULANT

<u>MATERIALS</u>

SUBSTRATE
ENCAPSULANT
PRECOATS
PRIMERS
CONDUCTOR

<u>PROCESSES</u>

CIRCUIT FABRICATION
SURFACE PREPARATIONS
- CLEANING
- PRIMER APPLICATIONS
- PRECOATING

ENCAPSULATION
- APPLICATION METHOD
- CURING CONDITIONS

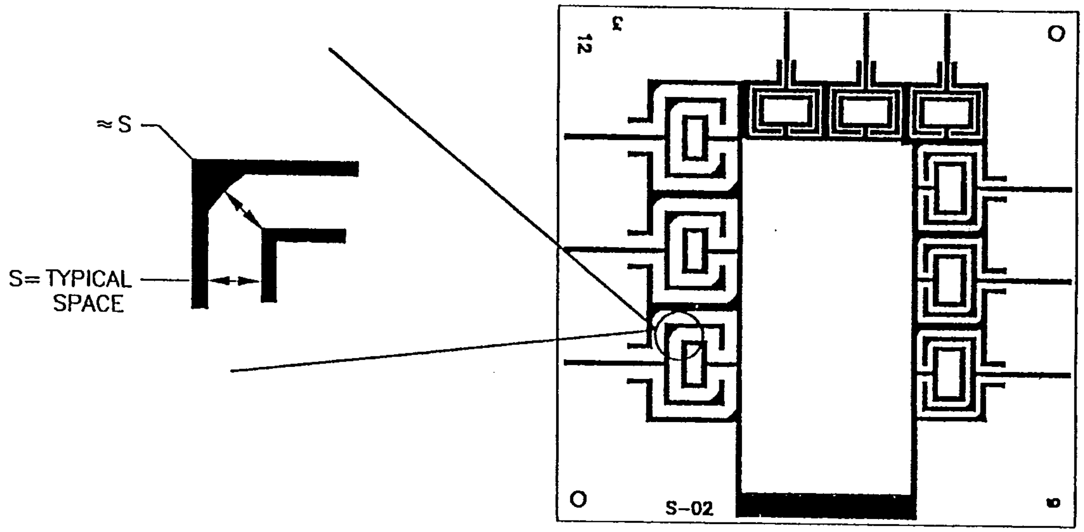
REPAIR/REWORK

<u>OPERATING FACTORS</u>

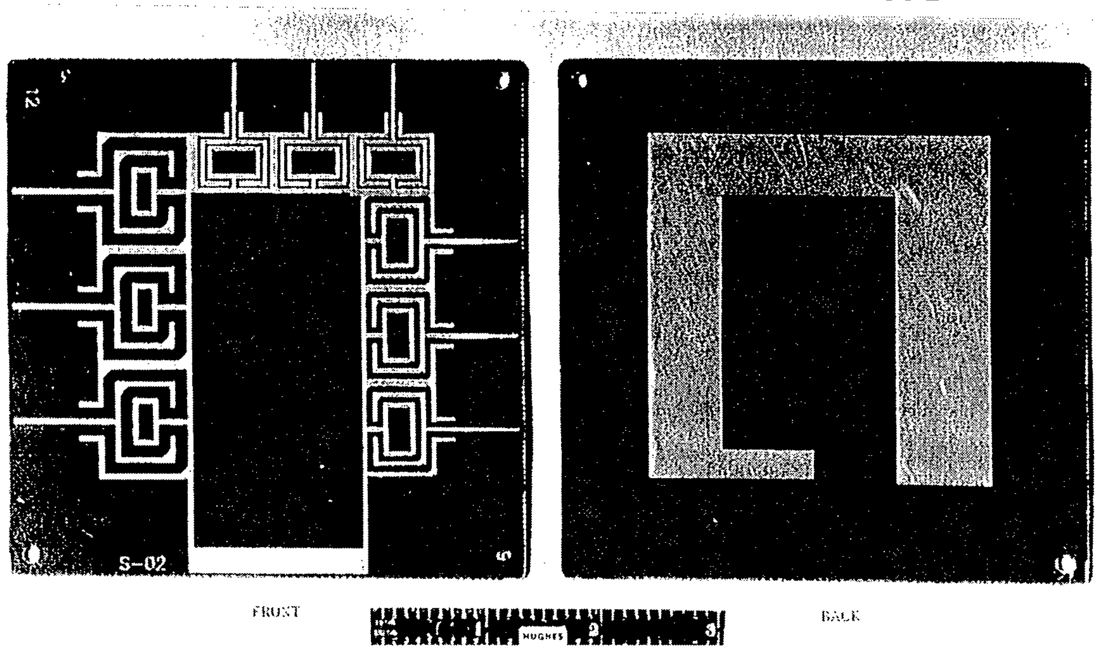
VOLTAGES
CURRENTS
ELECTRICAL LOSSES
TEMP. RANGE
THERMAL STRESS ($\Delta T°/\Delta t$)
ENVIRONMENTS

In the attached figures, the interconductor spacings of the square corner MTSs were set at three different values - 30, 60 and 120 mils. The spacing in the conductor corners matches the inter-electrode spacing. The backside contains a ground plane as shown. Section 2.4 gives results obtained with these structures.

SQUARE CORNERED – EQUISPACING (S–02)



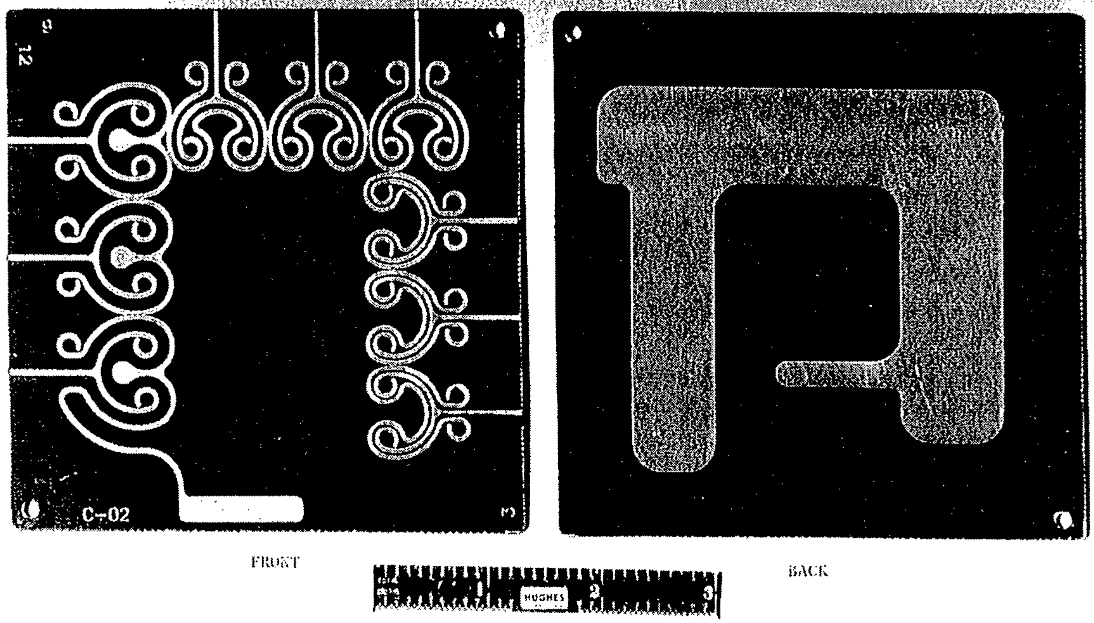
Test Structure – PWB Square Corners



91-03655

Test Structure – PWB Curved Corners

91-03666



Encapsulated Test Structure

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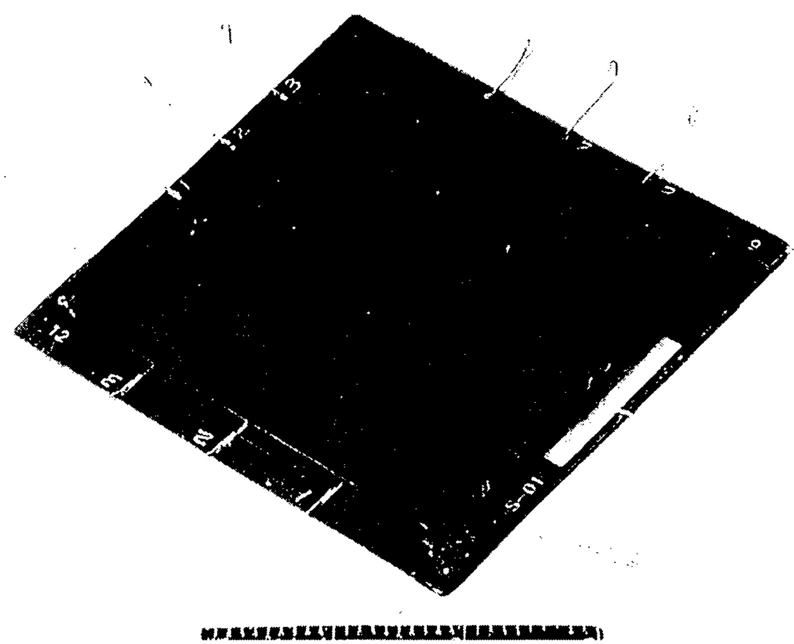
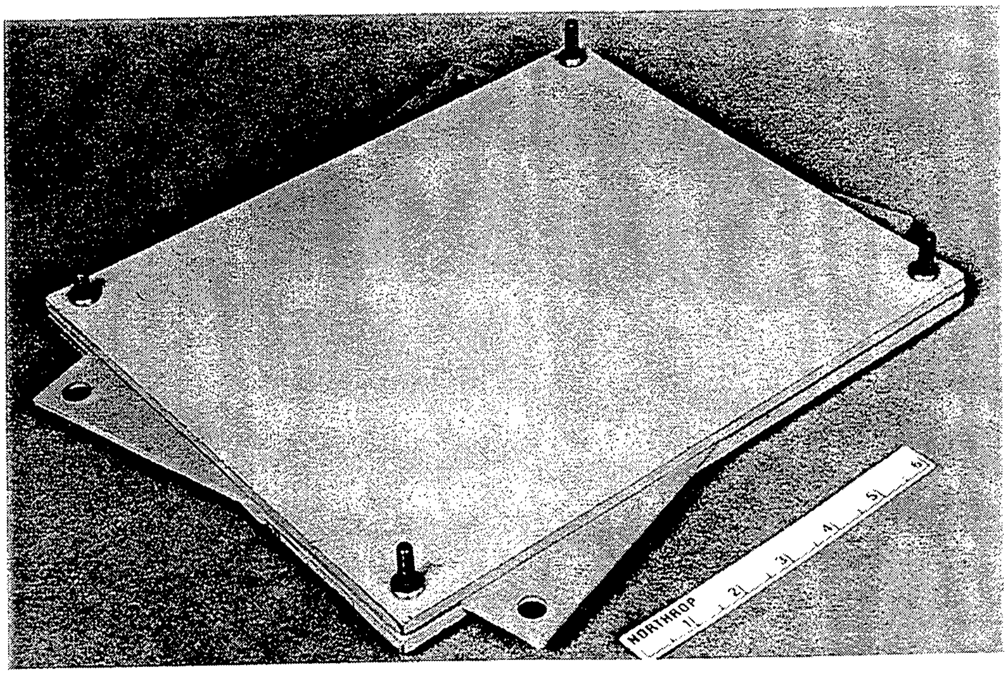
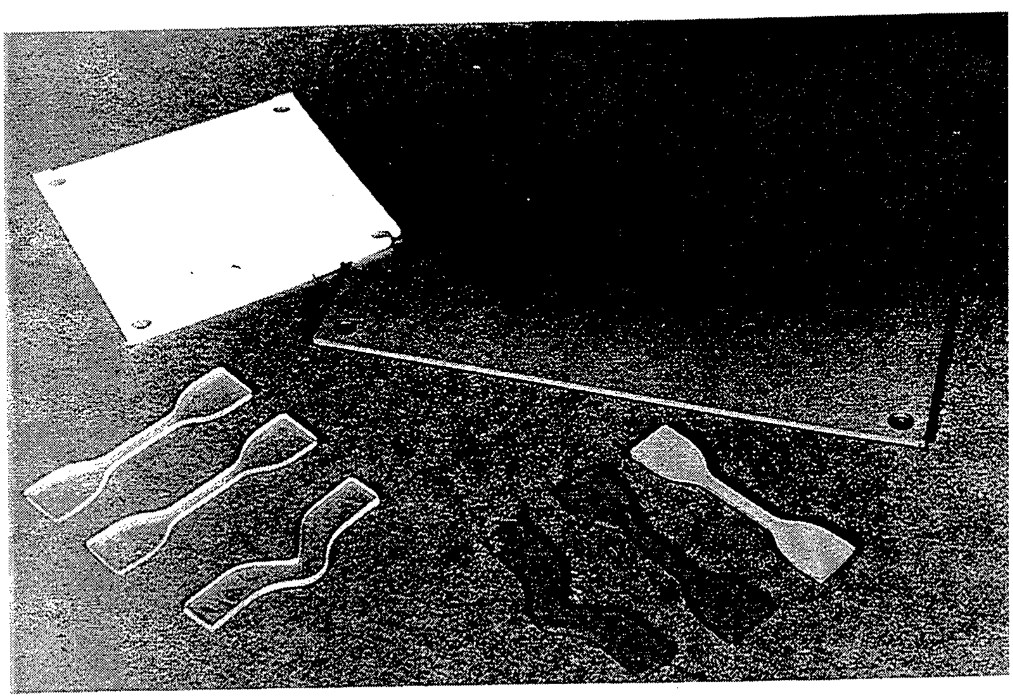


1.3 Silicone Rubber Test Structures

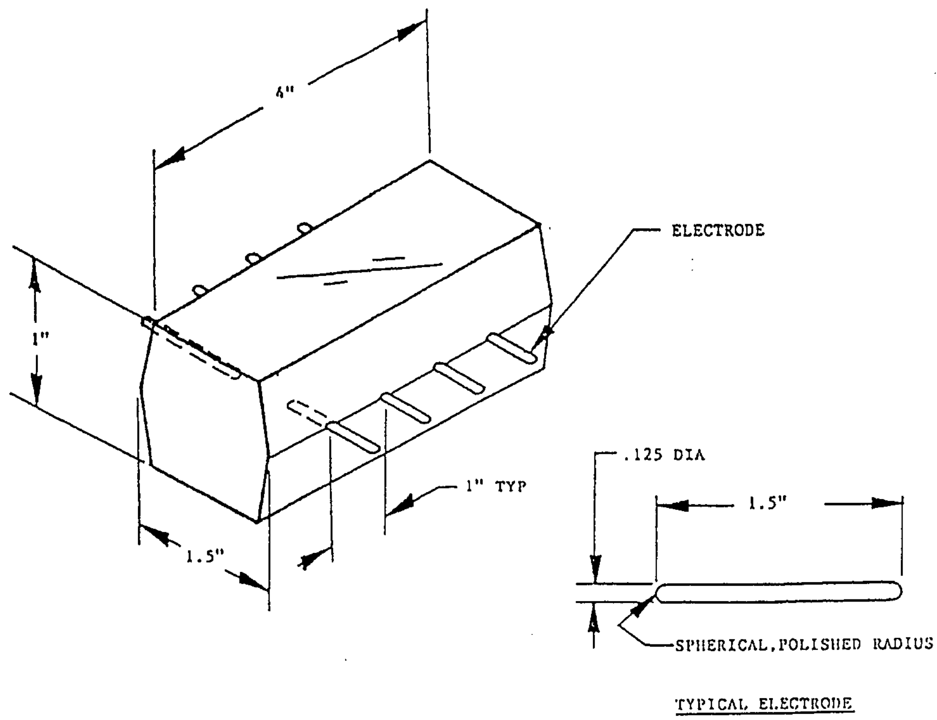
The 0.125 inch sheet is created by dispensing the silicone in a vacuum environment with three of the fixture sides taped. The plates of the fixture are teflon coated for ease of sheet removal. Both the tensile strength (symmetrical part) and tear strength test samples are die cut from the starting sheet. Dimensionally the test samples are per ASTMs D 412, 624 and 638. Note that the key to the tear strength samples is the quality and repeatability of the sharp inside "V" notch.

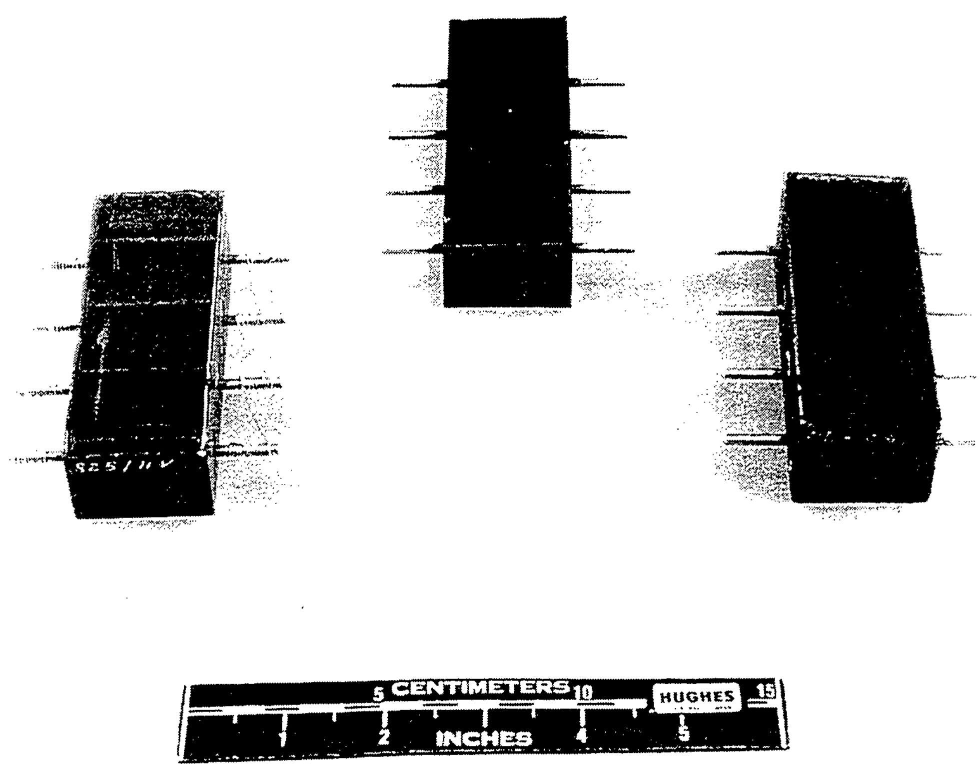




1.4 Encapsulated Electrode Pair Model Test Structure

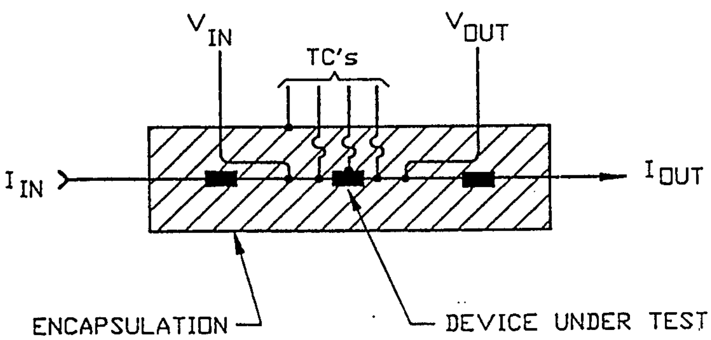
The Encapsulated Electrode Pair Model Test Structure was created to characterize the intrinsic high voltage behavior of encapsulants. The test structure provides a standard vehicle to evaluate corona and electrical breakdown characteristics (as well as thermal stresses) for various encapsulants. Note that the pairs can be individually activated or paralleled to obtain average value. Spacing between the pairs can be varied to suit.





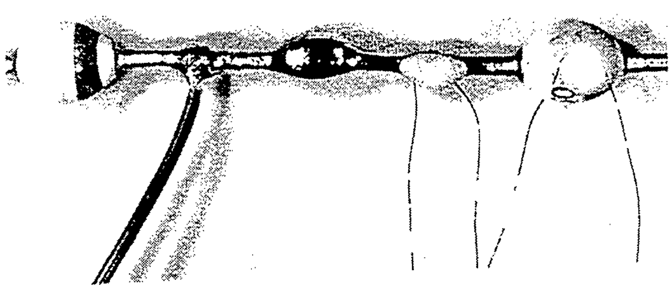
1.5 Diode Heat Transfer Model Test Structure

This Model Test Structure was devised to evaluate the heat path mechanisms of various diode constructions. Each test structure contains three diodes (in series) with thermocouples attached to the body and onto each of the leads of the center diode. The thermocouples are 0.003 inch diameter, type K. In addition to the thermocouples, a set of voltage monitoring leads (# 30 AWG copper) are attached to each lead of the center diode. The thermocouple positioning is intended to compare heat dissipation out the case versus out the leads - an important consideration in determining how to heat sink the diodes. The voltage monitoring leads serve to measure the forward voltage drop during testing of the three devices and to determine the power dissipation by the center diode during the testing. They also serve as a means of powering only the center diode while the two outboard diodes function as thermal insulators. Not shown is a fourth thermocouple located on the exterior of the epoxy block.

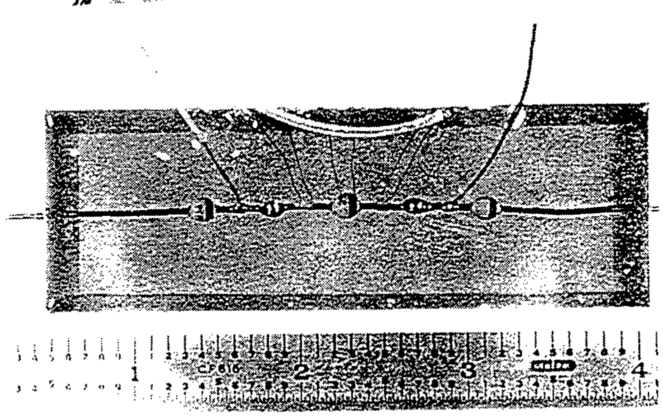


CONDITIONS

- STILL AIR, ROOM AMBIENT
- COLD PLATE (STILL AIR, ROOM AMBIENT)



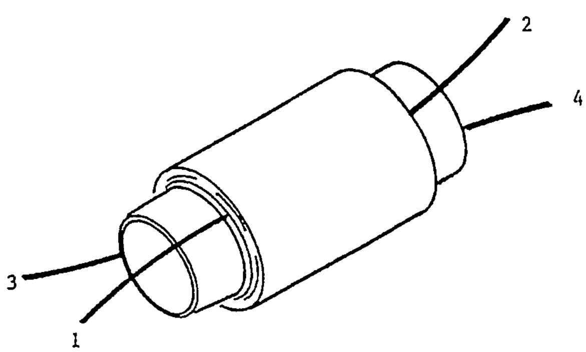
Diode, Thermocouple Assembly

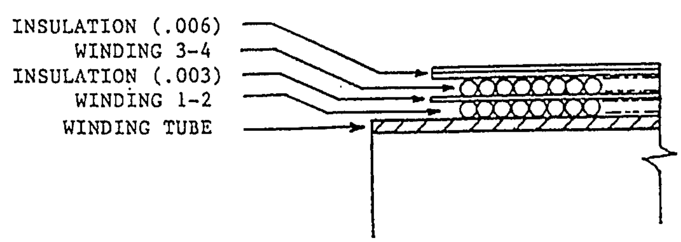


Encapsulated Test Structure

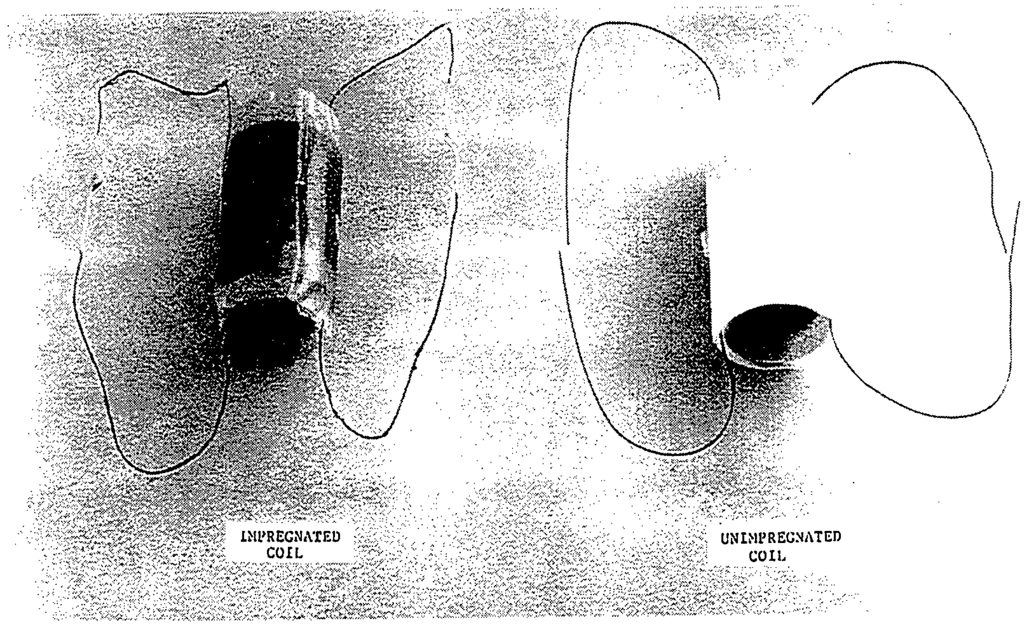
1.6 Impregnated Coils Model Test Structure

This test structure serves as a common base to evaluate the performance of encapsulants used with high voltage transformers. It uses a simple two winding, individual layer configuration that is common to most transformer designs. The windings can be series or parallel wired. Insulation/encapsulation combinations can be used to simulate differences in primary and secondary treatments of a transformer. The test structure is used to measure electrical breakdown characteristics, thermal performance etc.





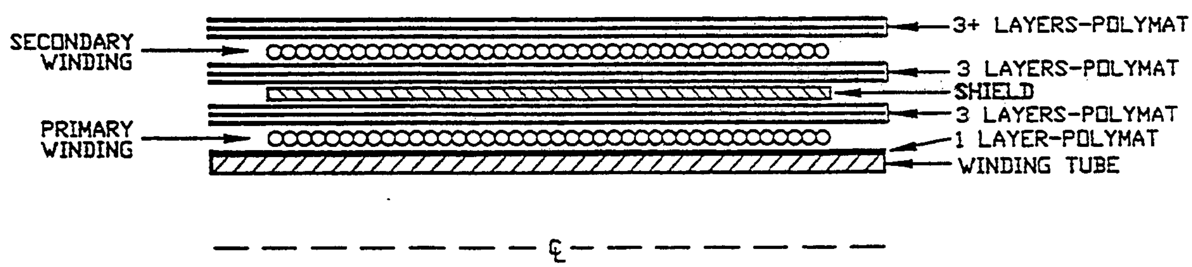
COIL CROSSECTION



1.7 Transformer Shielding Model Test Structure

Primary to secondary transformer shielding is frequently by trial and error to balance the decoupling needs of the circuit with the requirement for high transformer co-efficient of coupling. Metal foil and wire wound configurations are commonly used as shields; perforated foils or conductive paints are alternate methods. The illustrated model test structure was used to measure the effectiveness of various shielding configurations and further as an indicator of reliability by measuring corona and thermal performance.

CONSTRUCTION - SHIELD EVALUATION STRUCTURES



2.0 Test Results

This section of the report includes the results of specific studies that were performed as part of the Manufacturing Technologies for High Voltage Power Supplies program. These studies were performed to elucidate specific information about materials, design techniques, and components, to form a self-consistent body of information that would be useful to HVPS designers and manufacturers. In addition, they were undertaken to highlight issues that were thought to be of high importance, and to show other practitioners the types of information they should be collecting, and how to collect it. Information related to these topics is also contained in volumes 1 and 2 of this report, and in section 1.0 of this volume. It is recommended that, where feasible, other workers consider adopting the methods that were employed in this program, in order that they may use the data in this volume to compare to the data that they are collecting, and to form a "sanity check" on the conclusions that they draw.

2.1 Corona and Dielectric Breakdown Performance of Specific Materials using Encapsulated Electrode Pair Model Test Structures

During operation of a HVPS, its encapsulants are subjected to large DC and AC electric fields. The ability of the chosen encapsulation material to withstand these fields is of primary importance for the HVPS' reliability, and these properties are therefore of primary importance in materials selection. The use of fillers in encapsulants, as well as the specific manufacturing processing conditions chosen, will also effect these encapsulant electrical properties, and thus the critical electric field behavior of the encapsulant material also affects these selections. In turn, the packaging design will also be affected by the viscosity and thermal conductivity of the material; component selection will be influenced by the thermal properties of the material; and, electrical design will, in part, be dependent upon component selection issues. As is usual in HVPS design, the key variables interact in such a strong way that the values for each must be selected with the others in mind - another example of why a multifunctional, concurrent engineering team using the QFD approach is needed in HVPS design.

Two causes of material failure are to be expected in the event that the chosen encapsulant cannot withstand the electric fields present in the HVPS. The first is catastrophic breakdown (arcing) that occurs when the field exceeds the material's dielectric withstanding capability. The second is the slow, steady deterioration that is a consequence of corona discharge.

Corona discharge occurs when the contents of bubbles, occluded gases, or other materials within a region of high electric field gradients ionize to form a plasma. This energetic plasma is fed by electrostatic coupling to the source of the field, and it, in turn, degrades the surrounding materials by bond-breaking chemical reactions. In a polymer, the result of corona discharge is the formation of carbonaceous species adjacent to the electrode, on the walls of bubbles, along the sides of small cracks, or in the bulk of the material near the electrode. These carbon-rich, hydrogen- and oxygen-poor carbonaceous species resemble partially charred organics, and tend to be good electrical conductors. They can support a voltage similar to that on the adjacent wire or component that was the original source of the electric field, and can thus serve as the locus for further corona discharge damage.

Corona discharge damage tends to grow slowly and sporadically under conditions of electric field gradients that are not strong enough to cause immediate dielectric breakdown in the material. However, once a long enough corona path has been established in the material, the distance between the end of the corona path, a high voltage point, and a neighboring low voltage point, may become small enough that the electric field gradient becomes large enough to exceed the dielectric withstanding properties of the material. Then dielectric breakdown can occur. Thus corona discharge can lead to catastrophic HVPS failure during normal in-service operation. Corona discharge can also form partially conductive paths, like shunt resistors, between points in the HVPS that will degrade its electrical performance without causing catastrophic failure. Thus, understanding the critical electric field behavior of encapsulant materials prepared according to the proposed manufacturing processes is important - and the data is not generally available.

Fortunately, the types of MTSs and studies required to elucidate this information are relatively simple and are in the form of encapsulated electrode pairs. These MTSs are composed of pairs of electrodes with smooth, spherical ends that face each other across a well-defined gap, and are encapsulated in a block of the candidate resin. The MTS is shown in section 1.4 of this volume. For machining convenience the electrodes were made out of 1/8" diameter brass rod. Several electrode pairs were also incorporated in the same block of resin, spaced at one inch intervals in order to have multiple test specimens with the same inter-electrode spacing. Conversely, different spacings can also be tested in the same block of encapsulant for comparison purposes. Because corona discharge tends to be sporadic and highly dependent upon the physical details of the portion of the encapsulant that resides at or near the opposing electrode surfaces, multiple "runs", achieved by setting all of the electrode pairs in a single block of encapsulant to the same spacing, are highly recommended.

The mold used to make these MTSs can be built in two parts with a separation occurring along the line of the electrodes. After the mold halves are screwed together the electrodes are carefully positioned to the correct depths in the mold, and are then held in place with set screws. If the top of the mold is open, the inter-electrode spacings can be measured. It is recommended that, once the electrodes are encapsulated, the MTSs be X-rayed using conventional film X-ray techniques. It is relatively easy to place the MTSs directly on top of sheets of X-ray film, expose them in a cabinet X-ray system, and then confirm the inter-electrode spacings by measurements made directly from these X-ray film "contact prints." These MTSs can then be connected to appropriate electrical characterization equipment to study the critical electric field behavior of their encapsulants according to the procedure outline in other parts of this report.

The MTSs were immersed in Freon TF at room temperature to conduct our electrical characterizations. AC corona discharge (60 Hz) and breakdown voltage measurements were employed for these studies. 58 kV was the maximum breakdown voltage that could be measured. In the following tables, CIV stands for "corona inception voltage", which is the voltage at which the first evidence of corona discharge is seen. Once corona discharge has begun, it is often possible to reduce the applied voltage until the corona discharge count rate diminishes to zero. This lower voltage is called the "corona extinction voltage", or CEV in the following tables. VBD stands for "breakdown voltage."

Table 1 shows several sets of data taken on different Epon 825/HV MTSs. It gives an indication of the repeatability of the data. It also indicates that, within the limits imposed by our experimental conditions, this material has excellent critical electrical properties. Table 2 shows data on alumina-filled EPON 825/HV samples with two different levels of filler - one part EPON 825/HV to one part alumina in the first

Sample #	Electrode Spacing	Electrode Pair	CIV (kVAC)	CEV (kVAC)	VBD (kVAC)
EE.01	0.016"	A	-	-	>58 (6 min no fail)
	0.016"	B	-	-	>58 (6 min no fail)
	0.016"	C	-	-	>58 (6 min fail)
	0.016"	D	-	-	>58 (6 min fail)
EE.17	0.016"	A	-	-	>58 (75 min no fail)
	0.016"	B	-	-	>58 (75 min no fail)
	0.016"	C	-	-	>58 (75 min no fail)
	0.016"	D	-	-	>58 (75 min fail)
EE.02	0.032"	A	-	-	>58 (14 hrs no fail)
	0.032"	B	-	-	>58 (14 hrs fail)
	0.032"	C	-	-	>58 (14 hrs no fail)
	0.032"	D	-	-	>58 (14 hrs no fail)

Table 1. Critical electric field behavior for electrode pairs encapsulated in unfilled EPON 825/HV

Sample #	Electrode Spacing	Electrode Pair	CIV (kVAC)	CEV (kVAC)	VBD (kVAC)
EE.21	0.016"	A	50	-	50 (<6 sec)
(1:1)	0.016"	B	-	-	56 (instantaneous)
	0.016"	C	52	-	52 (after 30 sec)
	0.016"	D	54	-	54 (<6 sec)
EE.24	0.016"	A	44	-	44 (after 24 sec)
(1:2)	0.016"	B	50	-	50 (after 18 sec)
	0.016"	C	38	-	38 (after 24 sec)
	0.016"	D	-	-	56 (instantaneous)

Table 2. Critical electric field behavior for electrode pairs encapsulated in EPON 825/HV with Al_2O_3 filler in equal proportions (1:1) for sample EE.21 and with twice as much Al_2O_3 as EPON 825/HV (1:2) for sample EE.24.

case, and one part EPON 825/HV to two parts alumina filler in the second case. It is apparent from these data that the filler somewhat degrades the measured critical electrical properties of the EPON 825/HV, although it is well known that alumina filler greatly improves its thermal conductivity. Table 3 shows data on two runs made on Scotchcast 280 and Table 4 gives the results on comparable tests performed on other materials. The tests are summarized with the range of results shown in Table 5. Note that there are several products with greater voltage withstanding capability than the widely used Scotchcast 280 and 281.

Sample #	Electrode Spacing	Electrode Pair	CIV (kVAC)	CEV (kVAC)	VBD (kVAC)
Sample 1	0.016”	A	20	-	20 (after 24 sec)
	0.016”	B	18	-	18 (after 45 sec)
	0.016”	C	16	-	16 (after 12 sec)
	0.016”	D	-	-	21.4 (instantaneous)
Sample 2	0.016”	A	-	-	44 (instantaneous)
	0.016”	B	-	-	32 (instantaneous)
	0.016”	C	20	-	20 (after 24 sec)
	0.016”	D	-	-	29.4 (instantaneous)

Table 3. Critical electric field behavior for electrode pairs encapsulated in Scotchcast 280.

Sample #	Electrode Spacing	Electrode Pair	CIV (kVAC)	VBD (kVAC)
Scotchcast 281	0.016”	A	24	24.2 (instantaneous)
	0.016”	B	-	34 (instantaneous)
	0.016”	C	-	36 (after 24 sec)
	0.016”	D	24	24.2 (instantaneous)
Uralane 5753 sample 1	0.016”	A	38	38 (after 18 sec)
	0.016”	B	30	30 (after 6 sec)
	0.016”	C	32	32 (after 6 sec)
	0.016”	D	-	30 (after 30 sec)
Uralane 5753 sample 2	0.016”	A	24	24 (after 24 sec)
	0.016”	B	-	30 (instantaneous)
	0.016”	C	20	32 (instantaneous)
	0.016”	D	-	28.4 (instantaneous)
Stycast 2651	0.016”	A	52	52 (< 6 sec)
	0.016”	B	-	46.8 (instantaneous)
	0.016”	C	44	44 (after 10 sec)
	0.016”	D	-	41.5 (instantaneous)

Table 4. Critical electric field behavior for electrode pairs encapsulated in other materials.

Sample #	Electrode Spacing	Electrode Pair	CIV (kVAC)	VBD (kVAC)
Stycast 2850 FT	0.016"	A	18.7 CEV = 13.5	40.6 (instantaneous)
	0.016"	B	26 CEV = 15.7	36 (instantaneous)
	0.016"	C	34 CEV = 31	42 (instantaneous)
	0.016"	D	-	40 (instantaneous)
Scotchcast 2831	0.016"	A	-	>58 (failed between 5 and 16 min)
	0.016"	B	-	>58 (16 min no fail)
	0.016"	C	-	-
	0.016"	D	-	-
Ricotuff LV	0.016"	A	-	>58 (fail between 94 and 120 min)
	0.016"	B	-	>58 (fail between 94 and 120 min)
	0.016"	C	20	>58 (no fail between 94 and 120 min)
	0.016"	D	-	>58 (no fail between 94 and 120 min)

Table 4 (continued). Critical electric field behavior for electrode pairs encapsulated in other materials.

Encapsulant Type	Electrode Spacing (mils)	CIV (kVAC)	CEV (kVAC)	VBD (kVAC)
Scotchcast 280	16	20->32	-	20-32
Scotchcast 280	16	16-21	-	16-21
Scotchcast 281	16	24->36	-	24-36
Scotchcast 283/F025	16	-	-	>58
Stycast 2651	16	44-52	-	42-52
Stycast 2850 FT	16	19-34	14-31	36-42
Ricotuff LV	16	-	-	>58
Uralane 5753	16	24->34	-	24-34
Uralane 5753	16	30-38	-	30-38
Epon 825/HV	16	>58	-	>58
Epon 825/HV/Al_2O_3 (1:1)	16	50-54	-	50-56
Epon 825/HV/Al_2O_3 (1:2)	16	38-50	-	36-50

Table 5. Summary of comparative encapsulated electrode testing results on a variety of HVPS encapsulant materials.

2.2 Corona and Shield Effectiveness of Two Types of Transformer Electrostatic Shields Using Model Test Structures

A brief study was performed to assess the relative advantages and disadvantages of transformer electrostatic shielding layers made of wound wire versus those made of metal foil (see Section 1.7 of this volume for test structure illustrations). For this purpose, two different types of samples were studied. The first was an MTS in the form of a transformer with a shield between its coils. Two versions of this MTS were made, one with a 35 AWG wire-wound shield insulated with 15 mils of polymat between it and each coil, and the other with a 2 mil copper foil between the insulation layers. The second sample type was a set of transformers from the AMRAAM A3 design, with similar shield layers insulated with polymat. Both types of samples were impregnated with Epon 825/HV. All four sample types were subjected to AC corona discharge texting, performed at 60 Hz and with the samples in Freon TF at room temperature. The A3 transformers were also subjected to a shield effectiveness test per Mil-T-27.

The results of these tests are shown in Table 1, and both sample types showed similar AC corona discharge behavior. In each case, the AC corona inception voltage (CIV) was higher for the case of wire wound shields. In addition, the shield effectivess test showed a higher ratio for the case of wire-wound shields. We attribute this superior performance to the fact that the edges of the foil shield had not been rolled, but were in the original as-cut condition. The sharp edges can support high electric fields, resulting in CIV at lower voltages. In the absence of other considerations, it would appear that wound shields are superior to foil shields. The difference in CIV does not, however, invalidate the use of foil shields when overriding advantages accrue from the lesser thicknesses. There may be an advantage to testing an MTS under circumstances where foil shields are used with relatively high voltages, however.

	Shield Thickness (mils)	Insulation thickness (mils)	AC CIV (kVAC)	Shield effectiveness
MTS coil with wound shield	6.7 (35 AWG)	15	10.5	-
MTS coil with copper foil shield	2	15	6.2	-
A3 XFMR with wound shield	6.7 (35 AWG)	35	10.2	7.5 : 1
A3 XFMR with copper foil shield	2	35	8.5	5.8 : 1

2.3 Impregnated Coil Test Results

INTRODUCTION.

This activity had as its objective the demonstration of the MTS method as a means of evaluating high voltage insulation systems for their potential usefulness as insulation media in high voltage transformers. The following objectives provided the guidelines for this activity:

- o Evaluation of various electrical insulation combinations as HV insulations for transformers
- o Determination of the thermal stress behavior on the insulation system
- o Determination of the AC electrical loss characteristics of the candidates
- o Assessment of the processing characteristics of the various impregnants used in these evaluation

MTS DESIGN.

The Model Test Structure used in these evaluations is a single dielectric layer design using two single layer insulated copper wire windings as the electrodes. The single dielectric layer is formed using polymat, an open form, non-woven matting of polyester fibers. The structure is formed on an epoxy glass tube with an external wrapping of the polymat material covering the outer winding. Physical details of the MTS are shown in Section 1.6 and are outlined in Table 1. The structure is subsequently encapsulated with a reactive material to create the HV insulation system and to complete the MTS. MTS's before and after encapsulation are also shown in Section 1.6. It should be noted that the encapsulated unit shown was a prototype and was done using a vacuum-bag mold, not the metal molds used to fabricate the MTS's used in the evaluations described in the following sections.

The design of the test structure, in keeping with the MTS philosophy, embodies those physical elements which permit the evaluation of the intended functions and characteristics.

Winding Tube	1.0 dia. x 2.0 inch, 0.025 wall epoxy-glass
Insulation Layers	
• Under 1st winding / width	1 / 2.0 inches
• Between 1st - 2nd winding / width	1 / 2.0 inches
• Over 2nd winding / width	3 / 2.0 inches
Windings	
• 1st (No. 25 AHP)	68 turns (approx. 1.37m wide)
• 2nd (No. 25 AHP)	67 turns (approx. 1.37m wide)
End Margins	Approximate 0.3 inches

Table 1. Construction Details for the Transformer HV Insulation MTS's

CONSTRUCTION MATERIALS.

The materials used to construct the HV insulation systems are summarized below. As noted previously, the basic insulation systems under evaluation were a nonwoven fiber mat impregnated in-situ with a reactive resin material. Following are descriptions of these materials.

Polymat. The matting material used in the MTS's was a nonwoven polyester having the basic properties given in Table 2. The manufacturer of the material was Veratec, Inc.

Resin Impregnants. Four impregnants were included in these evaluations. All are epoxy based materials and are commercially available. All of the impregnants were used without fillers. The only supporting agent for the impregnants was the polymat material.

Epon 825/HV; EV Roberts and Associates. This material is a bisphenol A based epoxy cured with a combined aromatic and cyclic amine curing agent. The product is an unfilled rigid, glassy product having excellent high voltage properties with generally good other electrical properties. The material maintains these characteristics at high temperatures. The principal limitation for this material is its brittleness and hence the need for some form of reinforcement when subjected to moderate to severe mechanical and/or thermomechanical stresses. The material has a relatively short working(pot) life. This material was originally developed by Hughes, and in reinforced versions has been in use at Hughes as a HV material for more than 25 years. Typical properties for the formulation are given in Table 3. The mixing proportions used in fabricating the MTS's were

Epon 825	300 g
HV	54 g

Ricotuff LV(presently designated 1100); Ricon Resins, Inc. This material is an unfilled 1,2-butadiene based epoxy resin which cures via an anhydride mechanism. The material is stated to have excellent electrical properties, particularly AC loss characteristics, which are maintained at high temperatures. The material is also indicated to have superior adhesion to a variety of surfaces and materials. A primary limitation for the material are its properties which affect its behavior as an impregnant in high density and/or extended depth designs and configurations. Typical properties for the material are given in Table 3. The mixing proportions used in producing the MTS's were

Part A	200 g
Part B	100 g
catalyst	4 g

Araldite CY 9729 & HT 907; Ciba-Geigy Corp. This is a user formulated product in which the user selects the various ingredients and combining ratios to achieve specific properties. The resin system employs a cycloaliphatic epoxy resin reacted with an anhydride curing agent. The formulation used in these evaluations is unfilled. It was selected based on the manufacturer's literature which recommended its use in HV applications such as HV bushings and feedthroughs. The formula was also indicated to have good high temperature electrical properties, and processing attributes compatible with dense designs and extended

	Thickness	Tensile IMD	Strenght CMD	
Product No.	(mils)	(lbs/in)	(lbs/in)	Apparent Density
1620	3.0	23.0	4.6	0.78

MD - Machine direction
CMD - Cross machine direction

Table 2. Properties of the Non-Woven Polyester Matt from Veratec used in Constructing the MTS's

Property	Epon 825 HV	Ricotuff 1100	Araldite CY9729(1)	MR283 U000
tensile strenght (ksi)	8.5	2.9	8.1	6.4
tensile modulus (ksi)	470	132	1300	
elongation	2.4	3.3	10	4.8
coef. thermal expansion (ppm/°C)	50	125		
glass transistion (ppm°C)	130	-60°C to 60°C	137	
temp. rating (°C)				155°C
hardness (Shore D)	81	75	90	80
sp gravity	1.18	1.10		1.14
vol. resistivity (ohm-cm)	6.E16	2.E14	4.E13	1.5E16
diel. constant (1Hz) (60 Hz)**	4.6	3.3	4.2**	35**
Dissip. factor (10 Hz) (60 Hz)**	0.011	0.005	0.037**	0.004**

Note: These values include both manufacturer's data and data determined as part of this program.
(1) Based on sample containing 6 wt. % silica. used unfilled.

Table 3. Properties of the Resin Impregnants used in the Transformer HV Insulation Studies

depth configurations. Typical properties for this material are given in Table 3.; it should be noted that the properties given are for a formula containing 60 weight percent silica. No specific information for the unfilled formula was available, nor was this formula included in the Materials studies conducted as part of the Man-Tech Program. Following is the composition used in the MTS evaluations

CY 9729	200 g
HT 907	148 g
DY 9741	8 g

Scotchcast MR 283 - U000; 3M Corp. This is a relatively new product stated to have "excellent electrical properties" and "superior thermal shock resistance" (3M bulletin on Scotchcast Electrical Resins, 80-6105-6689-7 (9015.0)W-1, 1990), The material is an unfilled epoxy which cures via an anhydride mechanism. It was selected for these evaluations based on the stated electrical and thermal stress characteristics, and on its indicated process attributes. The combined working (pot) life and viscosities suggest the material to be compatible with dense and extended length designs. Properties for this material are shown in Table 3. The composition used in these evaluations was

Part A	200 g
Part B	100 g

EVALUATION SUMMARIES.

As previously noted, four general areas of characterization were addressed to establish the possible suitability of the four insulation systems as Transformer HV Insulation materials. These areas were in their order of presentation

Processability

- AC electrical loss
- HV characterization
- Thermal stress behavior

The results of the evaluations for each of these areas are presented in the following sections. An outline of the sequence used in these evaluations is shown in Figure 3.

A.Processibility.

Effective processing is both necessary and critical in achieving a reliable HV insulation system. The materials chosen must have processing characteristics which are compatible with the product design and the other materials , components and hardware used in the construction. This process compatibility includes the capability to process the various materials under conditions which will result in achieving the required product properties for the material being processed while satisfying the other compatibility considerations.

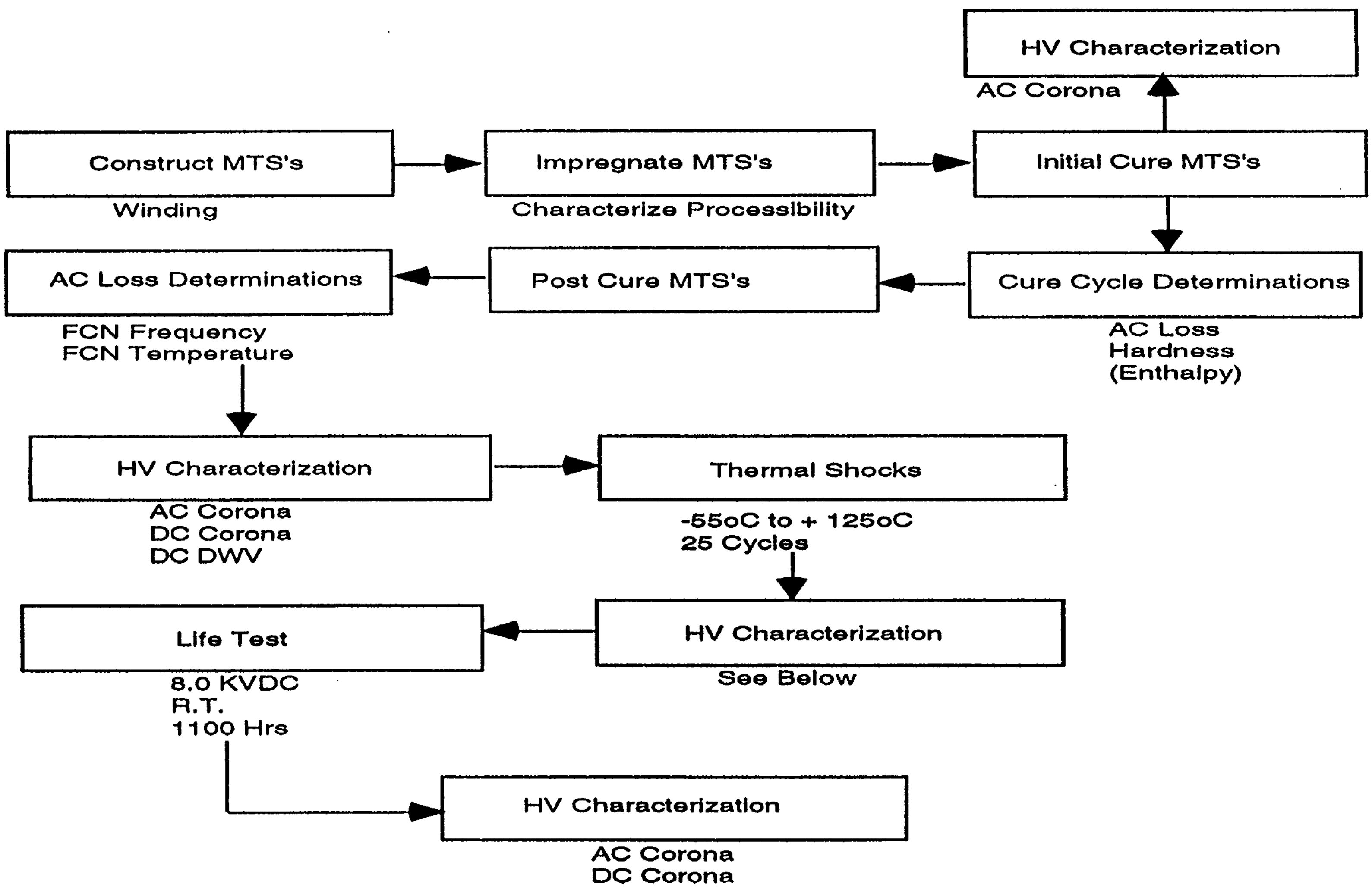


Figure 3: Sequence Used in Evaluating the Transformer HV Insulation Systems

To establish the processing characteristics for the four impregnants, an assessment was made of their behavior under proscribed process conditions. This included characteristics such as viscosities, working(pot) life, apparent ease/difficulty of impregnation and gel times. These characteristics are summarized both for individual properties and also for an overall assessment, the processability. The latter is a qualitative determination whose values are defined in Table 4.

As part of the processability evaluations, a series of determinations were made to determine the preferred cure schedules for the four impregnants.

A1 General Procedure.

The following general procedure was used with each of the four materials to impregnate the MTS's.

After forming the wire winding - polymat structure, each structure was placed in a cerro-type metal mold with the tube core filled with a Teflon rod. The inner diameter of the metal molds corresponded to the nominal outer diameter of the test structure, assuring that the impregnating resin would have polymat reinforcement.

The test structures in the molds were dried for 18 -24 hours at 105°C. After drying the mold assemblies which had been preheated to 85°C were placed in a vacuum chamber and evacuated to less than 10 microns. At this point the resin material was introduced into the molds while the mold assemblies were maintained under vacuum. All of the resin were degassed prior to introduction into the molds. Mixing details for each of the resin impregnants is given below. After introducing the resin, evacuation of the mold assemblies continued until the "bubbling " ceased or became minimal. The assemblies were then returned to 1. atmosphere and held for approximately 2. minutes. The assemblies were then re-evacuated. This cycling was performed at least two times for each material with additional cycling employed to achieve minimal, constant or no "bubbling".

After the vacuum filling process, the mold assemblies were placed in a circulating air oven to cure.

The cure schedules as well as the general processing characteristics for each of the impregnants are given in Table 4.

The specific mixing conditions for each of the resin materials is given below-

- Epon 825/HV: resin heated to 71°C(assure all crystals dissolved), add HV, preheated to 71°C
- Ricotuff LV: preheat Parts A and B to 71°C, then combine and mix, then add Part C and mix
- Araldite CY9729, etc.: preheat CY9729 and HT907 to 71°C, combine and mix, add DY9741(maintained at room-temperature), and mix
- MR283/U000: preheat Parts A and B to 71°C, combine and mix.

Process Characteristics	Epon 825 HV	Ricotuff LV	Araldite CY9729, HT907	Scotchcast MR283 U000
init. viscosity, $25^{o}C$ (cP)	900	35,000	-	3,300
init. viscosity, $71^{o}C$ (cP)	250	1400	<200	<200
working (pot) life (hrs.)	0.5-1	1.-2	2.-4	4.-8
gel time at the $71^{o}C$ (hrs.)	2.5	4.5	-	>12
init. cure (^{o}C - hrs)	71^{o}-16 + 121^{o}-4	71^{o}-6	100^{o}-16	93^{o}- 16
processbility*	3	4	1	1

* Qualitative assessment based on viscosity, working life, gel time: 1- excellent, 2 - very good, 3 - acceptable, 4- marginal, 5 - unacceptable.

Table 4: Processing Characteristics if the Resin Impregnants used in Constructuring the Transformer HV Insulation MTS's.

After completing the initial cure, the MTS's were removed from the molds and the initial test performed. A total of 10 MTS's were constructed for each of the resin impregnant - polymat combinations. In addition to the MTS's four discs of each of the impregnants were made for each of the materials. The discs were approximately 2 inches in diameter and 1/4 - 3/8 inches thick. The discs were processed simultaneously with the MTS's.

The initial tests performed included AC loss measurements and AC corona determinations. The results of these tests are presented in the sections covering these topics.

A2 Cure Schedule Determinations.

Cure schedule determinations were undertaken to establish that the resin systems used had been processed to optimal or near optimal properties.

Cure schedule determinations should be considered each time a new design and/or a new material combination is made. Such determinations result from the fact that the chemical reactions which produce the cured resin products are dependent on the thermal factors associated with both the resin and the product design and materials of construction. Any condition altering the thermal environment of the resin can change the rate at which the resin reacts(cures) and hence the rate at which the product properties are formed.

Several methods have used to monitor the curing(reaction) processes for resin materials. These include

o- mechanical loss tangent

o- electrical loss tangent(AC loss)

o- mechanical modulus

o- hardness

o- DC resistivity

o- several thermal analyses methods including enthalpy determinations

For these cure determinations, three methods were selected - 1) AC loss, 2) hardness, and 3) enthalpy determinations. However, only AC loss and hardness were used as continuing monitors, i.e., used at each measurement interval. The enthalpy determinations were made only initially and at the completion of all of the post curing exposures. Their primary function was as a confirmation that the reaction processes, as indicated by the monitors, were complete. In most circumstances enthalpy determinations would only be used in this manner since these measurements are much more time consuming (and expensive) than the other two methods.

Following are the procedures used in the cure schedule determinations, the results and a summary for the processing characteristics for the four HV insulation systems.

<u>AC loss determinations</u>. For these determinations an HP Impedance Analyzer, Model 4194A, was used in combination with an HP test fixture, Model 16047A. After each post cure interval, the MTS's were measured at 1.0, 10.0, 100.0 kHz and 1.0 MHz at 1.0 VRMS. For these measurements the lead ends of each winding were soldered together and

Post Cure Condition	Dissipation Factor			
	1.0 KHz	10. KHz	100. KHz	1. MHz
Initial cure, 16 hrs at 160^{o}F + 4 hrs at 250^{o}F	0.0046	0.0112	0.0174	0.0237
After approx. 120 days at room ambient	0.0049	0.0114	0.0175	0.0239
After 16 hrs at 250^{o}F	0.0045	0.0112	0.0173	0.0236

Sample No. 5-6

Table 5: Post Curing Effects on the Dissipation Factor of a Epon 825/HV-Polymat MTS

Post Cure Condition	Shore D Hardness	
	Initial	5 sec. Dwell
Initial cure, 16 hrs at 160°F + 4 hrs at 250°F	86	85
After approx. 120 days AI room ambient	86	85
After 16 hrs at 250°F	86	85

Disc No. 1

Table 6: Post Curing Effects on the Hardness of Epon 825/HV

Post Cure Effects on Ricotuff LV Dissipation Factor

Post Cure Condition	Dissipation Factor			
	1 KHz	10 KHz	100 KHz	1 MHz
Initial cure, 6 hrs at 160°F	0.03	0.055	0.07	-
43 hrs at 160°F	0.0061	0.0099	0.0126	0.0139
After ~60 days at ambient room conditions	0.0062	0.0109	0.0160	0.0175
20 hrs at 160°F	0.0064	0.0109	0.0150	0.0160
2 hrs at 230°F	0.0065	0.0106	0.0138	0.0149
2 hrs at 275°F	0.0063	0.0100	0.0127	0.0142
26 hrs at 275°F	0.0062	0.0093	0.0119	0.0140
44-1/2 hrs at 275°F	0.0061	0.0092	0.0117	0.0137
22-1/2 hrs at 320°F	0.0062	0.0093	0.0119	0.0139

*Sample No. 8-2.

Table 7: Post Curing Effects on the Dissipation Factor of a Ricotuff LV-Polymat MTS

Post-Cure Effects on Ricotuff LV Hardness

Post Cure Condition	Shore D Hardness*	
	Initial	5 sec. Dwell
Initial cure, 6 hrs at 160°F	50 (A2)	38 (A2)
43 hrs at 160°F	76	74
After ~60 days at ambient room conditions	76	74
20 hrs at 160°F	76	74
2 hrs at 230°F	76	74
2 hrs at 275°F	76	75
26 hrs at 275°F	80	78
44-1/2 hrs at 275°F	80	78
22-1/2 hrs at 320°F	80	79

*Disc No. 3

Table 8: Post Curing Effects on the Hardness of a Ricotuff LV

Post Cure Condition	Dissipation Factor*			
	1 KHz	10 KHz	100 KHz	1 MHz
After initial cure, 16 hrs at 212^oF	0.0071	0.0110	0.0124	0.0183
After initial post-cure, 118 hrs at 212^oF	0.0081	0.0121	0.0130	0.0126
Held at room ambient approx 115 days	0.0094	0.0147	0.0196	0.0227
After 66 hrs at 212^oF	0.0085	0.0126	0.0134	0.0156
After 6-1/2 hrs at 275^oF	0.0085	0.0126	0.0134	0.0154
After 47 hrs totasl at 275^oF	0.0083	0.0124	0.0131	0.0152
After 4 hrs at 320^oF	0.0084	0.0125	0.0132	0.0152
After 27 hrs total at 320^oF	0.0083	0.0123	0.0132	0.0152
After 1 3/4 hrs at 370^oF	0.0082	0.0122	0.0131	0.0152
After 12-3/4 hrs total at 370^oF	0.0080	0.0121	0.0129	0.0151

*Sample No. 7-1

Table 9: Post Curing Effects on the Dissipation Factor Araldite CY9729 HT907, DY9741-Polymat MTS.

Hardness During Post Cure

Post Cure Condition	Shore D Hardness*	
	Initial	5 sec. Dwell
After initial cure, 16 hrs at 212°F	83	81
After initial post-cure, 118 hrs at 212°F	85	83
Held at room ambient approx 115 days	85	83
After 66 hrs at 212°F	85	83
After 6-1/2 hrs at 275°F	85	84
After 47 hrs totasl at 275°F	86	84
After 4 hrs at 320°F	86	85
After 27 hrs total at 320°F	86	85
After 1 3/4 hrs at 370°F	86	85
After 12-3/4 hrs total at 370°F	86	85

Disc No. 2

Table 10: Post Curing Effects on the Hardness of Araldite CY9729, HT907, DY9741

Post-Cure Effects on Scotchcast MR283/U000 Dissipation Factor

Post Cure Condition	Dissipation Factor*			
	1 KHz	10 KHz	100 KHz	1 MHz
Initial cure, 16 hrs at 200°F	0.0058	0.0097	0.0124	0.0186
After ~ 30 days at ambient room conditions	0.0065	0.0114	0.0169	0.0200
45 minutes at 275°F	0.0075	0.0120	0.0167	0.0194
24 hrs at 275°F	0.0067	0.0103	0.0129	0.0162
42 hrs at 275°F	0.0068	0.0102	0.0129	0.0162
22-1/2 hrs at 320°F	0.0067	0.0102	0.0128	0.0164

*Sample No. 9-2.

Table 11: Post Curing Effects on the Dissipation Factor of a Scotchcast MR283/U000-Polymat MTS

Post Cure Condition	Shore D Hardness*	
	Initial	5 sec. Dwell
Initial cure, 16 hrs at 200°F	82	79
After ~ 30 days at ambient room conditions	82	79
45 min at 275°F	82	80
24 hrs at 275°F	84	82
42 hrs at 275°F	86	84
22-1/2 hrs at 320°F	86	84

Disc No. 3

Table 12: Post Curing Effects on the Hardness of Scotchcast MR283/U000

Resin Material	Enthalpy (J/gms	
	After Initial Cure	After All Post Curing
Epon 825/HV	0	0
Ricotuff LV	2 2	4
Araldite CY9729, etal	3 1	2
Scotchcast MR283/U000	8	1

Table 13: Enthalpy Values for the Resin Materials used in the Transformer HV Insulation MTS's

the leads of each of the two windings connected to the HI and LO terminals of the test fixture. All measurements were made at 22 - 25°C and 40 - 55% RH. After a post cure interval the MTS's were held at room ambient for 0.5 - 1.0 hours prior to testing. One MTS for each material system was used in these determinations.

Hardness. The method used employed both the initial hardness value and the value after a 5 second dwell. The use of the dwell value provides an additional indicator of the extent of the polymerization and cross - linking processes for the resin material. For these determinations the 2 inch diameter resin sample discs were used. After each post cure interval, the sample discs were returned to room ambient, and held for 1 hour prior to test. Hardness measurements were made using Shore durometers. For the measurement the durometer was applied to the disc with a 2. kg. load, and the initial and 5 second values recorded. A minimum of four such readings were made for each test. The reported values are the average of those readings. All measurements were made at 22 - 25°C and 40 - 55% RH. One disc of each resin material was used in the determinations.

Enthalpy. These determinations were made on samples taken after the initial cures for the four resin materials and after completion of all post curing exposures. The samples were taken from the disc used in the Hardness determinations. The sample size was approximately 0.5 grams, with less being used in the actual analysis. The analyses were performed using a DuPont Thermal Analyzer. The enthalpy measurements were made over the temperature range of -70 to 300°C in an air environment. The results reported are those for a single determination.

Post Cure Procedure. After the initial cures shown in Table 4., each material system was subjected to a series of post curing exposures. The exposure series for each material is given in the Results tables. It should be noted that there was an interruption between the initial curing and the post curing due to other program activities. During this time the MTS's were held at room - ambient. The initial temperature exposures after this interval are considered drying exposures.

A3 Results.

The results of the post cure determinations for the four material systems are presented as follows.

- Epon 825/HV: AC loss method, Table 5.; hardness Table 6.; enthalpy, Table 13.
- Ricotuff LV: AC loss method, Table 7.; hardness, Table 8.; enthalpy, Table 13.
- Araldite CY9729, etc.: AC loss method, Table 9.; hardness, Table 10.; enthalpy, Table 13.
- Scotchcast MR 283/U000: AC loss method, Table 11.; hardness, Table 12.; enthalpy Table 13.

From the results of these determinations the following post cure schedules were established for the four material systems. Also included here are the initial cure schedules; these are shown in parentheses.

- o Epon 825/HV: 4 - 8 hours at 250°F(16 hours @ 160° 4 hours @ 250°F)
- o Ricotuff LV: 20 - 28 hours at 275°F(6 hours @ 160°F)
- o Araldite CY9729, etc.: 4 - 8 hours @ 320°F(16 hours @ 212°F)
- o Scotchcast MR 283/U000: 20 - 24 hours @ 275°F(16 @ 200°F)

These post cure schedules were subsequently used to post cure the remainder of the MTS's for each of the material systems. For each system the maximum times were used. The dissipation factors(AC loss) for each of the MTS's for each of the material systems were measured before and after the post cures. These results are presented in Tables 14 through 21. Each of the material post cures included a material disc which had previously only been exposed to the initial cure conditions. Upon completion of the post cures, the hardness values of these discs were determined; the results are presented in Table 22.

A4 Summary.

Processibility includes two area of consideration:

- o impregnation characteristics
- o curing requirements

The impregnation characteristics for the four resin materials are presented in Table 4. The overall rankings for each of the materials are given in the table under Processibility. Both the Scothchcast MR283/U000 and the Araldite CY9729, etc. have process properties which make them very suitable as impregnants for HV transformers, etc.. Both have very low viscosities and long working(pot) lives.

The principal limitations of the Epon 825/HV material are the short working life and in large masses the potential for exothermic run - away. These characteristics must always be considered when using the material and the appropriate precautions taken.

The Ricotuff LV is a very marginal material as a HV transformer impregnant. This results from the very high room-temperature viscosity and the relatively high elevated temperature viscosities combined with the rates at which the viscosity increases with time and temperature. If this material is to be considered as a HV transformer impregnant these factors must reviewed in combination with the product design.

The curing procedure is also critical in determining the properties of the end product, e.g., HV transformers. The cure schedules developed here represent one of many schedules which can exist for each resin material . When developing such schedules, factors to be considered should include the temperature limits of all construction materials and components, thermo-mechanical stresses which can result from the curing temperatures, and the economics associated with the various time - temperature combinations under consideration. The cure schedules resulting from the determinations included these considerations.

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
5 - 1	0.0047	0.0114	0.0180	0.0243
5 - 2	0.0046	0.0113	0.0177	0.0236
5 - 3	0.0046	0.0114	0.0180	0.0238
5 - 4	0.0047	0.0114	0.0182	0.0243
5 - 5	0.0047	0.0113	0.0178	0.0239
5-6*	0.0049	0.0114	0.0175	0.0239
5 - 7	0.0047	0.0114	0.0180	0.0240
5 - 8	0.0046	0.0112	0.0178	0.0236
5 - 9	0.0045	0.0113	0.0180	0.0237
5 - 10	0.0047	0.0114	0.0181	0.0242

Conditions
Vac - 1.0 VRMS
24^{o}C
36%RH
*used in post cured determination

Table 14: AC Loss Characteristics for the Epon 825/HV-Polymat HV Insulation System Before Post Cure

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
5 - 1	0.0046	0.0112	0.0177	0.0240
5 - 2	0.0046	0.0111	0.0175	0.0233
5 - 3	0.0046	0.0113	0.0178	0.0235
4 - 5	0.0047	0.0113	0.0179	0.0240
5 - 5	0.0047	0.0112	0.0175	0.0237
5-6*	0.0045	0.0112	0.0173	0.0236
5 - 7	0.0046	0.0112	0.0176	0.0237
5 - 8	0.0045	0.0112	0.0176	0.0234
5 - 9	0.0046	0.0111	0.0176	0.0237
5 - 10	0.0047	0.0112	0.0177	0.0239

Conditions
Vac - 1.0 VRMS
24°C
25% RH
*used in post cure determination, values from these determinations; not cured this cycle

Table 15: AC Loss Characteristics for the Epon 825/HV-Polymat HV Insulation System After Post Cure (8 Hours at 250°F)

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
8-2*	0.0063	0.0109	0.0160	0.0715
8-3	0.0060	0.0110	0.0161	0.0178
8-4	0.0061	0.0110	0.0161	0.0176
8-5	0.0060	0.0111	0.0160	0.0174
8-6	0.0060	0.0111	0.0161	0.0176
8-7	0.0060	0.0110	0.0161	0.0176
8-8	0.0061	0.0110	0.0161	0.0174
8-9	0.0060	0.0111	0.0161	0.0177
8-10	0.0061	0.0110	0.0159	0.0175
11	0.0061	0.0111	0.0161	0.0176

Conditions
Vac - 1.0 VRMS
23°C
23% RH
*used in post cure determination

Table 16: AC Loss Characteristics for the Ricotuff LV- Polymat HV Insulation System Before Post Cure

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
8-2*	0.0062	0.0093	0.0119	0.0140
8-3	s			
8-4	s			
8-5	0.0060	0.0096	0.0121	0.0141
8-6	s			
8-7	0.0061	0.0095	0.0121	0.0143
8-8	0.0061	0.0095	0.0121	0.0142
8-9	0.0060	0.0095	0.0121	0.0143
8-10	0.0063	0.0095	0.0120	0.0140
8-11	0.0061	0.0096	0.0121	0.0143

Conditions
Vac - 1.0 VRMS
23°C
46% RH
*used in post cure determinations, values from those determinations; not cured this cycle
s- shorted previous HV test

Table 17: AC Loss Characteristics for the Ricotuff LV- Polymat HV Insulation System After Post Cure (28 Hours at 275°F)

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
7-1*	0.0094	0.0147	0.0196	0.0227
7-2	0.0090	0.0143	0.0193	0.0224
7-3	0.0088	0.0142	0.0193	0.0227
7-4	0.0090	0.0144	0.0195	0.0222
7-5	0.0090	0.0144	0.0194	0.0222
7-6	0.0091	0.0144	0.0194	0.0221
7-7	0.0089	0.0144	0.0194	0.0227
7-8	0.0089	0.0143	0.0194	0.0228
7-9	0.0091	0.0144	0.0195	0.0224
7-10	0.0090	0.0144	0.0194	0.0220

Conditions
Vac - 1.0 VRMS
25°C
25% RH
*used in post cure determinations,

Table 18: AC Loss Characteristics for the Araldite CY9729, etc. - Polymat HV Insulation System Before Post Cure

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
7-1*	0.0084	0.0125	0.0132	0.0152
7-2	0.0081	0.0121	0.0129	0.0146
7-3	0.0078	0.0118	0.0127	0.0152
7-4	s			
7-5	0.0079	0.0120	0.0128	0.0151
7-6	0.0079	0.0120	0.0126	0.0151
7-7	0.0078	0.0120	0.0125	0.0152
7-8	0.0080	0.0120	0.0129	0.0151
7-9	0.0080	0.0120	0.0126	0.0151
7-10	0.0080	0.0121	0.0123	0.0151

Conditions
Vac - 1.0 VRMS
24^{o}C
44% RH
*used in post cure determinations, values from those determinations; not cured this cycle.
s- shorted previous HV test

Table 19: AC Loss Characteristics for the Araldite CY9729, etc. - Polymat HV Insulation System After Post Cure (8 Hours at 320^{o}F)

Dissipation Factor

MTS No.	1.0 kHz	10.0 kHz	100.0 kHz	1.0 MHz
9 - 1	s			
9-2*	0.0065	0.0114	0.0169	0.0200
9 - 3	-			
9 - 4	0.0064	0.0114	0.0171	0.0203
9 - 5	0.0064	0.0114	0.0169	0.0198
9 - 6	s			
9 - 7	s			
9 - 8	0.0067	0.0118	0.0180	0.0216
9 - 9	0.0067	0.0116	0.0176	0.0212
9 - 10	0.0067	0.0116	0.0177	0.0213

Conditions
Vac - 1.0 VRMS
$23^{o}C$
44% RH
*used in post cure determinations.
s- shorted previous HV test

Table 20: AC Loss Characteristics for the Scotchcast MR283/U000- Polymat HV Insulation System Before Post Cure

Dissipation Factor

MTS No.	1.0 KHz	10.0 KHz	100.0 KHz	1.0 MHz
9-1	s			
9-2*	0.0068	0.0102	0.0129	0.0162
9-3	s	-	-	
9-4	0.0067	0.0102	0.0130	0.0163
9-5	0.0067	0.0103	0.0130	0.0163
9-6	s			
9-7	s			
9-8	0.0066	0.0102	0.0129	0.0164
9-9	0.0066	0.0102	0.0129	0.0163
9-10	0.0067	0.0103	0.0129	0.0163

<u>Conditions</u>
Vac - 1.0 VRMS
$23^{o}C$
38% RH
*used in post cure determinations, values from these determinations; not cured this cycle.
s- shorted previous HV test

Table 21: AC Loss Characteristics for the Scotchcast MR283/U000- Polymat HV Insulation System After Post Cure (24 Hours at $275^{o}F$)

	Shore D Hardness			
	Initial		5 Second	
Resin Material	Before	After	Before	After
Epon 825 / HV	86	86	85	85
Ricotuff LV	76	81	74	79
Araldite CY9729, etc	85	86	83	85
Scotchcast MR283/U000	82	86	79	84

Measurement Conditions

22 - 25°C

20- 50% RH

Table 22: Hardness Values for the Resin Materials Before and After Post Cures of the MTS's

A comparison of both the Dissipation Factors and the Hardness of the MTS's and discs used in the cure schedule determinations with those resulting when the selected cure schedules were applied to the other MTS's for each of the materials show the values to be essentially equal. These equalities confirm the validity of the selected schedules. The confirmation is based on the method used in the initial determinations.

In establishing the cure schedules, the time - temperature exposures were continued beyond the point where dissipation factors and the hardnesses had become constant. The absence of further change in these values with continued exposure indicates that the chemical reactions responsible for these properties had ceased, i.e., the material was "fully cured". As was done here, the schedule determinations should be extended beyond the "constant value" point for the parameter being monitored, e.g., dissipation factor. Beyond this point in time, temperature or combinations of both, there should be no change in the monitored value if the cure is completed. This completion of cure was confirmed by the enthalpy determinations where the reactive energy levels were at or near zero for each of the four materials.

The interruptions in the cure schedule determinations is not recommended. If occurring as it did here, it should not affect the results of the determinations. Whether occurring with or without interruption, the cure schedule determination should be continued to and beyond the "constant value" point. Delays in the determination may result in off-sets of a monitor value, as was experienced here for the dissipation factors for three of the materials; such off-sets should not affect the final determination. The exception to the negligible effects of delays would be those material which are highly reactive at low or room - temperatures. Cure schedule determinations for these materials must be made without interruption.

The results of the cure schedule determinations have shown both the dissipation factor and the hardness measurements to be effective methods for monitoring the curing process. Other methods, some of which were mentioned previously, can also be effectively used. The choice should be based on the availability of suitable equipment and personnel.

B AC Loss Characterizations.

The AC losses occur within a transformer HV insulation system where ever AC voltages are present. An awareness of these losses is important from two considerations.

First, such losses contribute to the total losses within the transformer. These dielectric losses can become significant accounting for several percent of the total transformer losses for insulation systems high AC losses, depending on the insulation system and the operating conditions.

The second consideration associated with the AC losses are the heating effects which can result from these losses. Such heating can under certain conditions lead to thermally induced failure of the insulation material due to temperature run-away effects.

Because of these considerations, it is important to know the AC loss characteristics of a transformer HV insulation system over the operating/requirements temperature ranges and at the operating frequencies. Since the losses increase with increasing temperature, it is generally most important to know the AC losses at room-temperature and at the maximum operating temperature at the operating frequency.

The following sections describe a method for making AC loss measurements as a function of temperature and frequency and the results of such measurements for the four transformer HV insulation systems.

B1 Method for AC Loss Determinations as a Function of Temperature and Frequency.

Several methods can be used for determining the AC losses of electrical insulations at various temperatures and frequencies. This section describes one method using a 2-terminal test configuration and an impedance analyzer to determine the AC losses or dissipation factors (DFs). This method, including equipment and procedures, is described in detail in the following section. Also presented are the results obtained using this method with the four HV insulations.

B1.1 Measurement Method.

AC losses are affected by all of the dielectric materials present in the measurement circuit in addition to the test sample. These materials include the electrical insulations of the test fixture and the cables and interconnections. Since the losses of these materials can be reflected in the measured value of the test sample, it is important to know the contribution of these losses to the measured value. Hence, the following requirements should be imposed when making AC loss measurements:

> 1 - fixture, etc. losses should not distort or obscure the measured value of the test device or MTS over the temperature and frequency ranges for the measurement.
>
> 2 - fixture, etc. losses should be known over the range of measurement conditions.

Determining Item 2, in conjunction with the resolution requirements for the loss measurement of the test device, will define the requirements for Item 1.

Knowing the general ranges of the dissipation factors for the four MTS types from the cure schedule determinations, the measurement method began with the characterization of the loss characteristics of a special test fixture (Hughes design) to be used in these determinations.

The test fixture (detailed in Volume 2 section 1.3.2 and further shown here as Figure 4) is an aluminum box having isolated BNC connectors as the input-output terminals with each connector connected directly to a clip for attaching the test sample. Each isolated BNC could be either isolated from the box or grounded to it via a selector switch. The purpose in such switching is to permit control over coupling capacitances and their attendant AC losses for the fixture. The isolated BNCs were Teflon insulated to minimize losses at both room and elevated temperatures. The cabling from the test fixture to the exterior of the temperature chamber was Teflon insulated semi-rigid coax rated at 50 ohms. This cabling was also selected to minimize and control losses. The semi-rigid was connected to the impedance analyzer using R-58 coax having polyethylene insulation. The total cabling length was approximately 2 feet. It should be noted that these loss measurements employed a 2-terminal configuration. Previous AC loss measurements comparing 2- and 4-terminal configurations showed equivalent results for the frequency ranges and resolution requirements for these determinations.

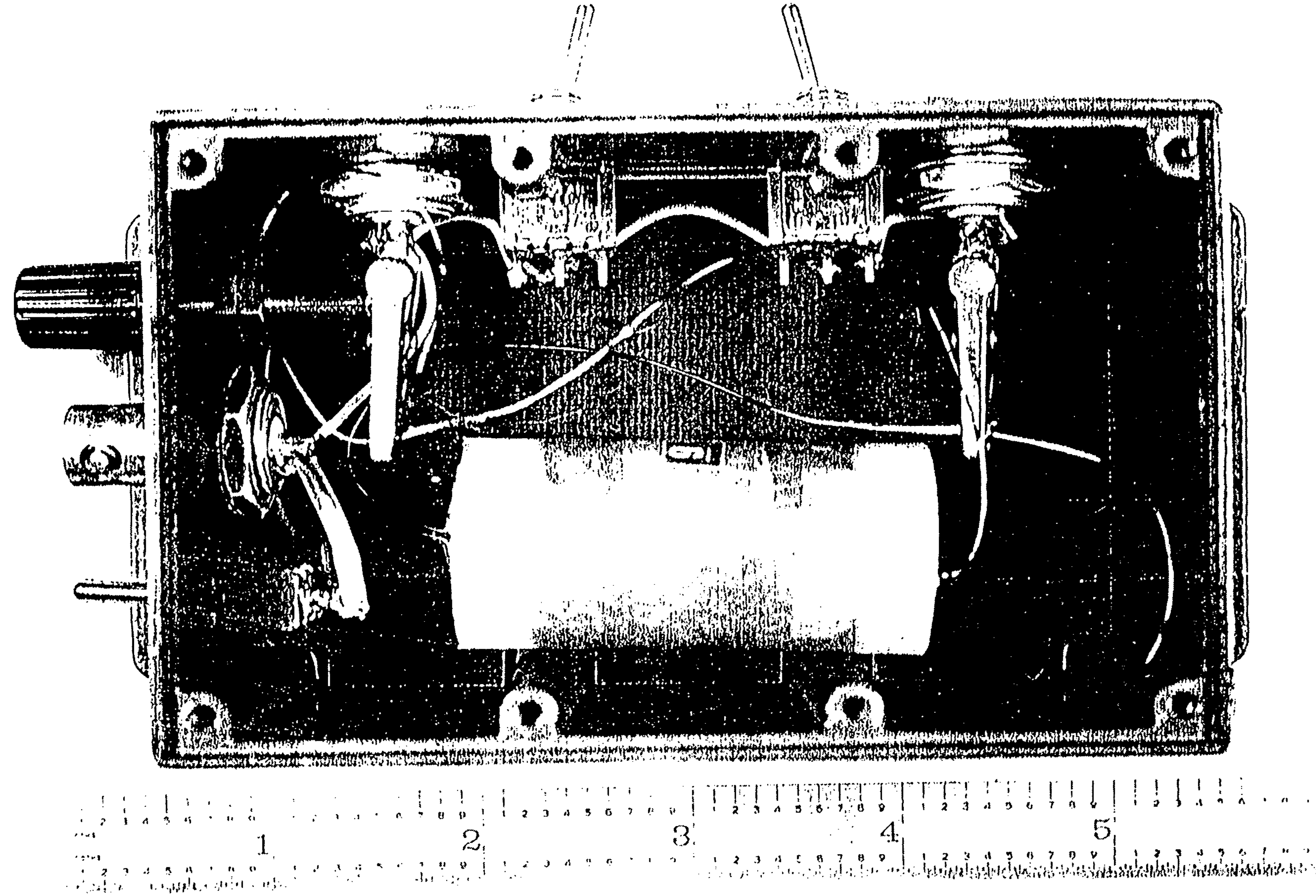


Figure 4. Test Fixture For Measuring The AC Losses Of Transformer Impregnated Coil MTSs At Elevated Temperatures

An HP16047A test fixture was used as the "standard" for comparing with the Hughes fixture. This fixture is intended specifically for impedance measurements of components. The fixture normally employees a 4-terminal configuration; however, for these evaluations it was reconfigured to 2-terminal. The new configuration was assessed to show that this alteration had no effect on its performance for these tests.

Impedance Analyzer.

The impedance analyzer used in all of the determinations was an HP 4291A, having a frequency range of 5 Hz to 13 MHz and a dissipation factor resolution of 0.0000.

Measurement Conditions.

Seven frequencies and five temperatures were used in these evaluations. These are given in Table 23. All measurements were made at 1.0 Vrms.

Measurement Procedures and Results.

The Dissipation Factor determinations were performed in two stages. In the initial stage, the loss characteristics (DFs) of the Hughes fixturing were determined to establish any correction factors required to accurately characterize the DFs of the four HV insulation systems.

In the second stage, the DFs were determined for the HV insulation MTSs under the conditions noted in Table 23.

The DF characterization of the Hughes fixture was begun by comparing the DFs using the two test fixtures and three test samples. The test samples were

- o variable air capacitor: APC 100L, 100pF.
- o silver mica capacitor per Mil-C-39001: 1.2nF, 500V.
- o control MTS, constructed of polymat and Epon 825/HV(No.2-1).

Using the three test samples and the seven frequencies, the DFs were measured in the two test fixtures, the Hughes and the HP, at room-temperature. The results of these measurements are presented in Table 24.

Table 25. compares the differences in DFs resulting for the two test fixtures with the three test samples. The difference in DF between the two fixtures, C1, becomes the correction factor for subsequent MTS dissipation factor measurements,

$$C1 = DF(Hughes) - DF(HP) \qquad (1)$$

These determinations indicate the Hughes fixture to be usable to 200 kHz without the need for correction. At 500 kHz, the use of correction factors would depend in part on the magnitude of the device being measured. At 1 MHz, the use of correction factors would generally be required, but this would depend on the values of the device being measured.

Next, the AC loss characteristics of the Hughes fixture were determined over the combined temperature and frequency ranges. For these determinations the variable air capacitor was used. This capacitor which has alumina and air insulators exhibits essentially constant

Temperatures	Frequencies
25^{o}, 65^{o}, 85^{o} and 125^{o} C	1.0k, 10.0k, 50.0k 100.0k, 200.0k, 500.0k and 1.0 MHz

All measurements made at 1.0 Vrms

Table 23: Measurement Conditions for the AC Loss Determinations of the Transformer HV Insulation MTS's

Dissipation Factors

Freq(KHz)	Ag mica capacitor		Control coil MTS		Air Capacitor	
	Hughes	H.P.	Hughes	H.P.	Hughes	H.P.
1.0	-0.0004	-0.0004	0.0056	0.0056	-0.0009	-0.0011
10.0	0.0004	0.0003	0.0128	0.0128	-0.0004	-0.0005
50.0	0.0004	0.0004	0.0193	0.0194	0.0000	0.0000
100.0	0.0006	0.0003	0.0238	0.0217	0.0001	0.0000
200.0	0.0006	0.0003	0.0238	0.0236	0.0002	0.0000
500.0	0.0010	0.0004	0.0262	0.0257	0.0003	0.0001
1000.0	0.0024	0.0006	0.0309	0.0293	0.0007	0.0002

Measured at - 1.0 VRMS
24^{o} - 25^{o}C

Table 24: A Comparison of the Dissipation Factors using the Hughes Test Fixture and the HP 16047A Test Fixture

Dissipation Factor Differences

Freq (KHz)	Ag mic cap	Control coil MTS	Air cap	Avg Difference,C1
1.0	0.0000	0.0000	0.0002	0.0001
10.0	0.0001	0.0000	0.0001	0.0001
50.0	0.0000	-0.0001	0.0000	0.0000
100.0	0.0002	0.0000	0.0001	0.0001
200.0	0.0003	0.0002	0.0002	0.0002
500.0	0.0006	0.0005	0.0002	0.0004
1000.0	0.0018	0.0016	0.0005	0.0013

Table 25: Dissipation Factor Differences Existing between the Hughes Test Fixture and the HP 16047A Test Fixture

capacitance and dissipation factors over the temperature and frequencies used in these determinations. Any deviation for the room-temperature DF values are considered attributable to the Hughes fixture. Such differences would then become a second correction factor, C2, to be considered when determining the DFS of the various MTSs.

$$C2 = DF((f(x)\&T^*(y)) - DF((f(x)\&T^*(R.T.)) \qquad (2)$$

The results of the DF determinations of the Hughes fixture for the evaluation temperatures and frequencies are given in Table 26. Also, included are the correction factors, C2.

These temperature - frequency results show:

- o AC losses, i.e., test fixture dissipation factors, for the Hughes fixture to be very low over the test ranges of temperatures and frequencies.

- o in the extreme case the fixture variation is within 0.0001 units of the DF resolution of the LRC analyzer (0.0002 units measured vs. 0.0001 units as the resolution limit).

Given these results and the range of dissipation factors for the MTSs being measured, the use of the C2 correction factor is not necessary to accurately describe the AC losses of the various insulation systems over these temperature and frequency ranges.

MTS Measurements and Results.

Two MTSs for each of the HV insulation systems were used to characterize the DFs for the conditions described in Table 23. The Hughes fixture and the procedure described above were used in each determination. It should be noted that no corrections were made for the frequencies through 200 kHz. The measured correction factors through this frequency range were within 0.0002 units of the LRC analyzer resolution limit. The use of the 0.0004 correction at 500 kHz is of questionable value and is done here primarily to demonstrate the correction method. The use of the correction factor at 1.0 MHz was considered necessary to accurately describe the DFs for the HV insulation systems. The correction factors used were those given in Table 25. The C2 correction factors, given in Table 26, were considered inconsequential and were therefore not used to establish the DFs for the four MTS types.

Following are the results observed for the AC loss characteristics as a function of temperature and frequency for the four transformer HV insulation systems.

Epon 825/HV - Polymat (see Table 27. and Figure 5 - 9.).

- o to 85°C reductions in DF occur at all test frequencies. These reductions range approximately 20 to 60 percent with the larger reductions occurring at the lower frequencies.

- o at 106°C, the DF is increasing at 1.0 and 10.0 kHz, and then decreasing at 50.0 kHz and above.

- o at 126°C, the DF is increasing from 1.0 through 50.0 kHz. At 100.0 kHz and above, the DF continues to decrease.

Temp (ºC)	Freq. (KHz)	D.F. Measured	D.F. @ 24ºC	D.F. Correction C2
24º	1.0	-0.0009	-0.0009	0.0000
	10.0	-0.0004	-0.0004	0.0000
	50.0	0.0000	0.0000	0.0000
	100.0	0.0001	0.0001	0.0000
	200.0	0.0002	0.0002	0.0000
	500.0	0.0003	0.0003	0.0000
	1000.0	0.0007	0.0007	0.0000
65º	1.0	-0.0009	-0.0009	0.0000
	10.0	-0.0004	-0.0004	0.0000
	50.0	0.0001	0.0000	0.0001
	100.0	0.0002	0.0001	0.0001
	200.0	0.0002	0.0002	0.0000
	500.0	0.0004	0.0003	0.0001
	1000.0	0.0007	0.0007	0.0000
85º	1.0	-0.0008	-0.0009	0.0001
	10.0	-0.0003	-0.0004	0.0001
	50.0	0.0002	0.0000	0.0002
	100.0	0.0001	0.0001	0.0001
	200.0	0.0002	0.0002	0.0000
	500.0	0.0003	0.0003	0.0000
	1000.0	0.0007	0.0007	0.0000
106º	1.0	-0.0007	-0.0009	0.0002
	10.0	-0.0004	-0.0004	0.0001
	50.0	0.0001	0.0000	0.0001
	100.0	0.0002	0.0001	0.0001
	200.0	0.0002	0.0002	0.0000
	500.0	0.0004	0.0003	0.0001
	1000.0	0.0007	0.0007	0.0000
127º	1.0	-0.0007	-0.0009	0.0002
	10.0	-0.0003	-0.0004	0.0001
	50.0	0.0002	0.0000	0.0002
	100.0	0.0001	0.0001	0.0000
	200.0	0.0002	0.0002	0.0000
	500.0	0.0004	0.0003	0.0001
	1000.0	0.0007	0.0007	0.0001

All measurements at 1.0 VRMs

Table 26: Factors for the Variable Air Capacitor (APC 100L) as a Function of Temperature and Frequency using the Hughes Test Fixture

Temp	Freq.	D.F. Measured		D.F. - Corrected	
(^{o}C)	(KHz)	5 - 1	5 - 2	5 - 1	5 - 2
26°	1.0	0.0062	0.0061	0.0062	0.0061
	10.0	0.0132	0.0130	0.0132	0.0130
	50.0	0.0173	0.0173	0.0173	0.0173
	100.0	0.0183	0.0183	0.0183	0.0183
	200.0	0.0192	0.0193	0.0192	0.0193
	500.0	0.0203	0.0207	0.0199	0.0203
	1000.0	0.0222	0.0221	0.0209	0.0208
64°	1.0	0.0028	0.0028	0.0028	0.0028
	10.0	0.0065	0.0065	0.0065	0.0065
	50.0	0.0110	0.0110	0.0110	0.0110
	100.0	0.0135	0.0134	0.0135	0.0134
	200.0	0.0160	0.0161	0.0160	0.0161
	500.0	0.0191	0.0191	0.0187	0.0187
	1000.0	0.0224	0.0223	0.0211	0.0210
85°	1.0	0.0028	0.0028	0.0028	0.0028
	10.0	0.0048	0.0048	0.0048	0.0048
	50.0	0.0078	0.0078	0.0078	0.0078
	100.0	0.0100	0.0098	0.0098	0.0098
	200.0	0.0125	0.0125	0.0125	0.0125
	500.0	0.0163	0.0163	0.0159	0.0129
	1000.0	0.0205	0.0203	0.0192	0.0190
106°	1.0	0.0053	0.0054	0.0053	0.0054
	10.0	0.0058	0.0059	0.0058	0.0059
	50.0	0.0071	0.0072	0.0071	0.0072
	100.0	0.0085	0.0086	0.0085	0.0086
	200.0	0.0104	0.0105	0.0104	0.0105
	500.0	0.0139	0.0139	0.0135	0.0135
	1000.0	0.0183	0.0182	0.0170	0.0169
126°	1.0	0.0075	N.T.	0.0075	
	10.0	0.0078	N.T.	0.0078	
	50.0	0.0085	N.T.	0.0085	
	100.0	0.0092	N.T.	0.0092	
	200.0	0.0105	N.T.	0.0105	
	500.0	0.0131	N.T.	0.0127	
	1000.0	0.0172	N.T.	0.0159	

N.T. - Not tested
All measurements at 1.0 VRMS

Table 27: Dissipation Factors for the Epon 825/HV - Polymat Transformer HV Insulation System as a Function of Frequency and Temperature - Both measured and Corrected Values

DISSIPATION FACTORS OF MTS'S AT 24°C

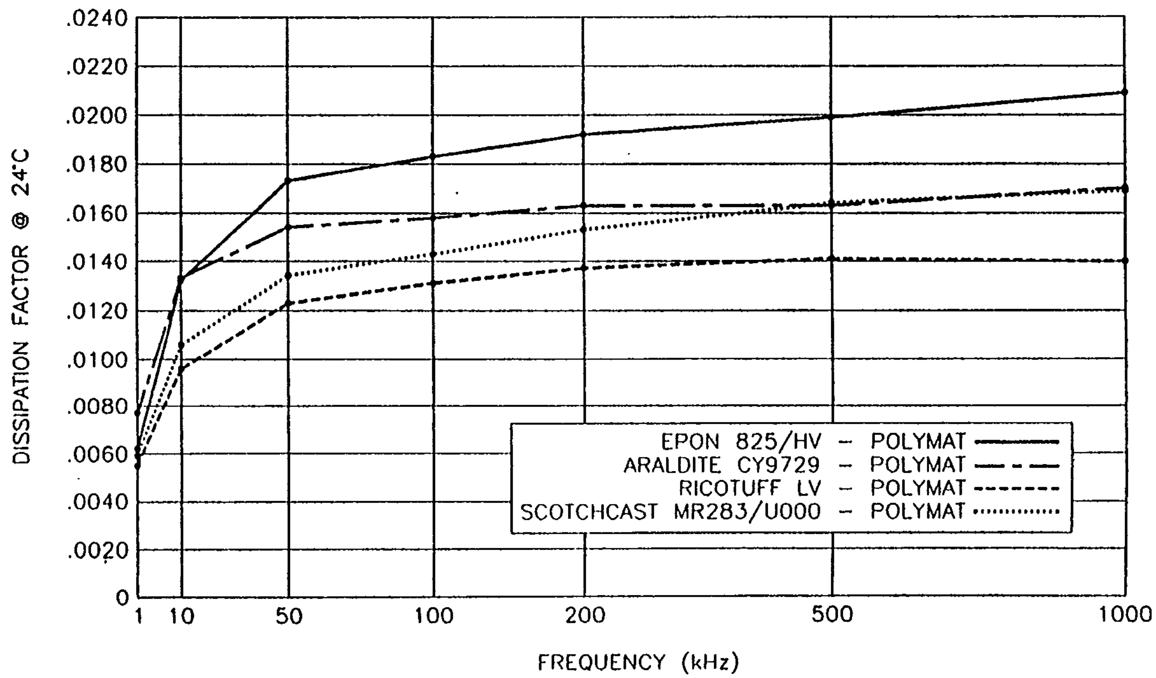


Figure 5
Dissipation Factors of MTS's At 24°C

DISSIPATION FACTORS OF MTS'S AT 65°C

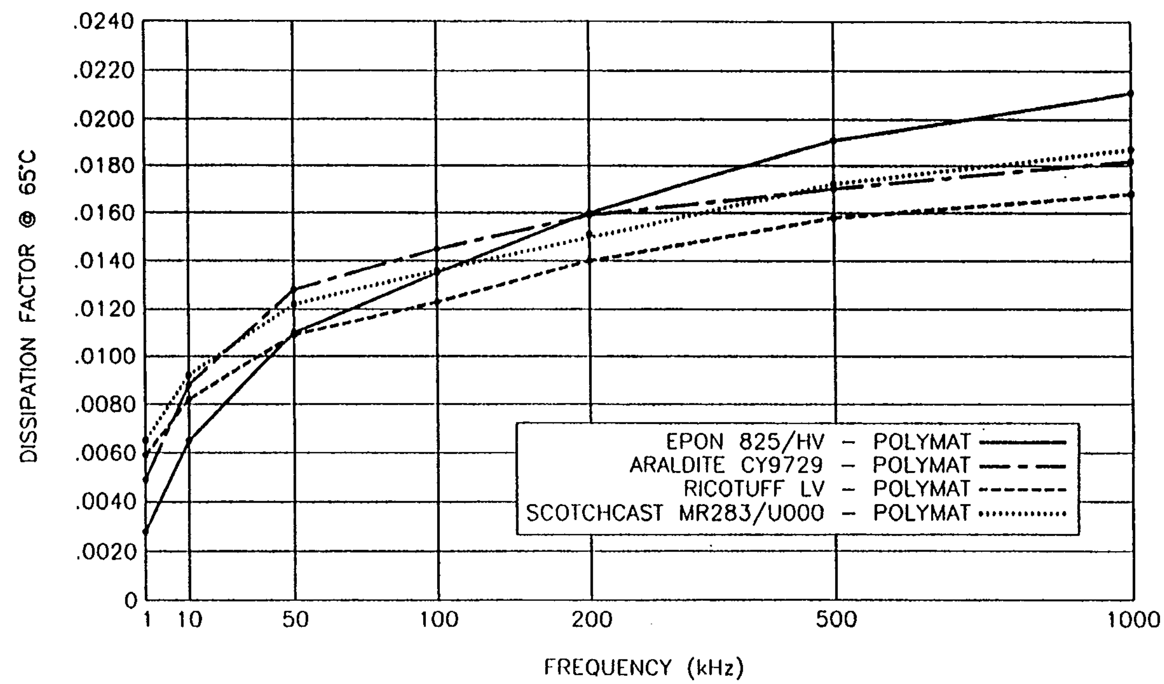


Figure 6
Dissipation Factors of MTS's At 65°C

DISSIPATION FACTORS OF MTS'S AT 85^{O}C

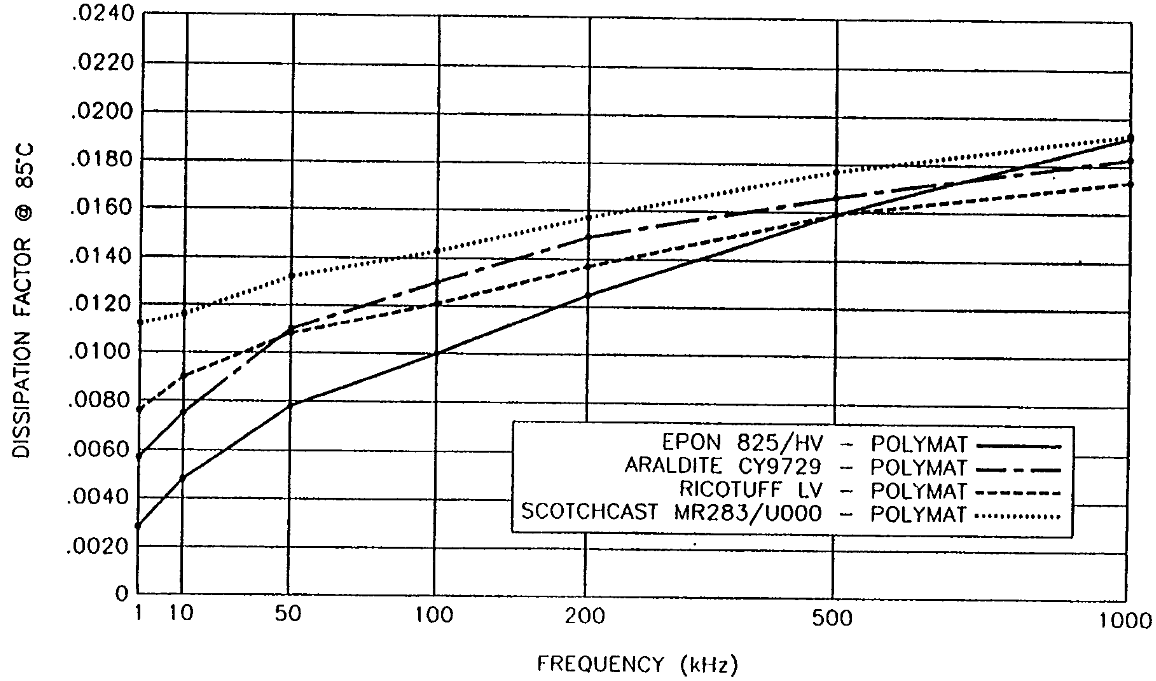


Figure 7
Dissipation Factors of MTS's At 85^{O}C

DISSIPATION FACTORS OF MTS'S AT 106°C

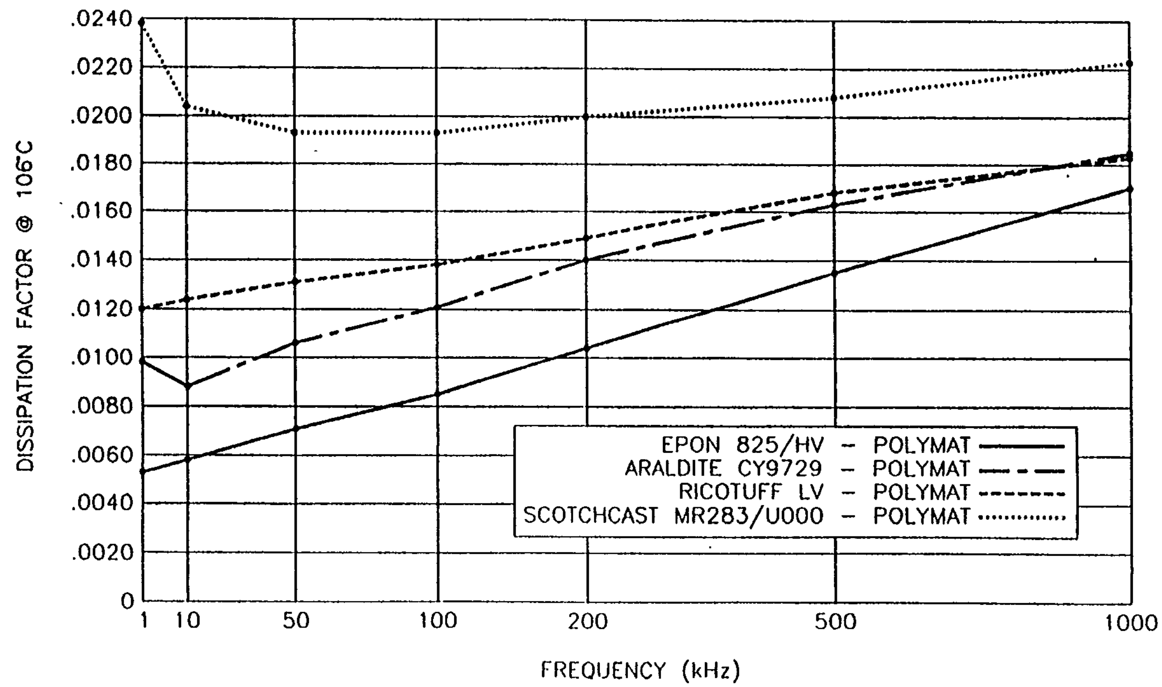


Figure 8
Dissipation Factors of MTS's At 106°C

DISSIPATION FACTORS OF MTS'S AT 126°

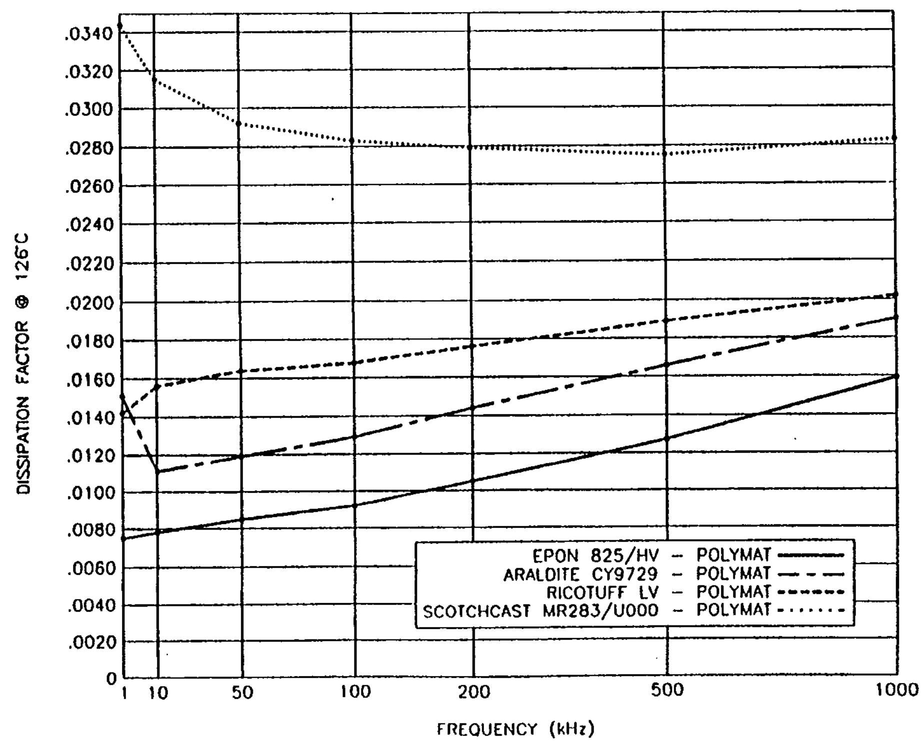


Figure 9
Dissipation Factors of MTS's At 126°C

Ricotuff LV - Polymat (see Table 28. and Figure 5 - 9.).

- o to 65°C, a slight increase in DF exists at 1.0 kHz with slight reductions present from 10.0 kHz through 200.0 kHz. At 500.0 kHz and above the DF increases approximately 20 percent.

- o at 85°C, the DF is increasing through 10.0 kHz. From 50.0 kHz and above, the DF is essentially constant vis-à-vis the 65°C values.

- o at 106°C, the DF increases significantly, approximately 30 - 80 percent, from 1.0 kHz through 50.0 kHz when compared to the 85°C values. At 100.0 kHz and above, the DFs increase slightly with respect to the 85°C values.

Araldite CY 9729, etc. - Polymat (see Table 29. and Figure 5 - 9.).

- o to 85°C, reductions in DF occur at all test frequencies through 500.0 kHz. These reductions range from approximately 10 to 50 percent with the larger reductions occurring at the lower frequencies. At 1.0 MHz, there is a slight in the DF.

- o at 106°C, the DF has substantially increased at 1.0 and 10.0 kHz, the increases ranging from approximately 30 to 100 percent. At 50.0 kHz and above the DFs are essentially unchanged vis-à-vis the 85°C values.

- o at 126°C, the DF increases at all test frequencies. The increases at 1.0 and 10.0 kHz are substantial when compared with the 85°C values, approximately 70 and 30 percent respectively. At 50.0 kHz and above, the increases are minimal when similarly compared, typically less the 5 percent.

Scotchcast MR 283/U000 - Polymat (see Table 30. and Figure 5 - 9.).

- o DFs experienced increases at each elevated temperature at all test frequencies. The exceptions were slight reductions of approximately 10 percent occurring at 65°C at 10.0 through 100.0 kHz.

- o at 85°C, the DF at 1.0 kHz increased nearly two times the 26° and 65°C values. At 10.0 kHz and above, the increases were between 5 and 10 percent

- o at 106°C, the DFs at 1.0 and 10.0 kHz increased approximately 200 and 175 percent respectively relative to the 85°C values. At 50.0 kHz and above, the increases were substantial ranging from approximately 30 to 50 percent with the larger increases occurring at the lower frequencies.

- o at 126°C, the DFs increased substantially again from those occurring at 106°C, ranging from approximately 125 to 140

Temp	Freq.	D.F. Measured		D.F. - Corrected	
(^{o}C)	(KHz)	5 - 1	5 - 2	5 - 1	5 - 2
26^{o}	1.0	0.0055	0.0054	0.0055	0.0054
	10.0	0.0096	0.0098	0.0096	0.0098
	50.0	0.0123	0.0126	0.0123	0.0126
	100.0	0.0131	0.0134	0.0131	0.0134
	200.0	0.0137	0.0141	0.0137	0.0141
	500.0	0.0145	0.0150	0.0141	0.0146
	1000.0	0.0153	0.0159	0.0140	0.0146
65^{o}	1.0	0.0059	0.0059	0.0059	0.0057
	10.0	0.0082	0.0080	0.0082	0.0080
	50.0	0.0109	0.0108	0.0109	0.0108
	100.0	0.0123	0.0122	0.0123	0.0122
	200.0	0.0140	0.0140	0.0140	0.0140
	500.0	0.0162	0.0165	0.0158	0.0161
	1000.0	0.0181	0.0187	0.0168	0.0177
85^{o}	1.0	0.0076	0.0074	0.0076	0.0074
	10.0	0.0090	0.0087	0.0090	0.0087
	50.0	0.0108	0.0106	0.0108	0.0106
	100.0	0.0121	0.0119	0.0121	0.0119
	200.0	0.0137	0.0136	0.0137	0.0136
	500.0	0.0163	0.0165	0.0159	0.01160
	1000.0	0.0186	0.0190	0.0173	0.0177
106^{o}	1.0	0.0120	0.0116	0.0120	0.0116
	10.0	0.0124	0.0120	0.0124	0.0120
	50.0	0.0131	0.0128	0.0131	0.0128
	100.0	0.0138	0.0133	0.0138	0.0133
	200.0	0.0149	0.0146	0.0149	0.0146
	500.0	0.0172	0.0171	0.0168	0.0167
	1000.0	0.0196	0.0198	0.0183	0.0185
126^{o}	1.0	0.0142	N.T.	0.0142	
	10.0	0.0156	N.T.	0.0156	
	50.0	0.0164	N.T.	0.0164	
	100.0	0.0168	N.T.	0.0168	
	200.0	0.0176	N.T.	0.0176	
	500.0	0.0193	N.T.	0.0189	
	1000.0	0.0215	N.T.	0.0202	

N.T. - Not tested
All measurements at 1.0 VRMS

Table 28: Dissipation Factors for the Ricotuff LV - Polymat Transformer HV Insulation System as a Function of Frequency and Temperature - Both measured and Corrected Values

Temp	Freq.	D.F. Measured		D.F. - Corrected	
(^oC)	(KHz)	5-1	5-2	5-1	5-2
26^o	1.0	0.0077	0.0080	0.0077	0.0080
	10.0	0.0133	0.0138	0.0133	0.0138
	50.0	0.0154	0.0159	0.0154	0.0159
	100.0	0.0158	0.0162	0.0158	0.0162
	200.0	0.0163	0.0166	0.0163	0.0166
	500.0	0.0167	0.0172	0.0163	0.0168
	1000.0	0.0183	0.0183	0.0170	0.0170
65^o	1.0	0.0049	0.0059	0.0049	0.0059
	10.0	0.0088	0.0090	0.0088	0.0090
	50.0	0.0128	0.0132	0.0128	0.0132
	100.0	0.0145	0.0150	0.0145	0.0150
	200.0	0.0159	0.0164	0.0159	0.0164
	500.0	0.0174	0.0181	0.0170	0.0177
	1000.0	0.0195	0.0197	0.0182	0.0184
85^o	1.0	0.0057	0.0065	0.0057	0.0065
	10.0	0.0075	0.0076	0.0075	0.0076
	50.0	0.0110	0.0112	0.0110	0.0112
	100.0	0.0130	0.0131	0.0130	0.0131
	200.0	0.0149	0.0152	0.0149	0.0152
	500.0	0.0170	0.0177	0.0166	0.0173
	1000.0	0.0196	0.0197	0.0183	0.0184
106^o	1.0	0.0098	0.0130	0.0098	0.0130
	10.0	0.0088	0.0092	0.0088	0.0092
	50.0	0.0106	0.0109	0.0106	0.0109
	100.0	0.0121	0.0123	0.0121	0.0123
	200.0	0.0140	0.0143	0.0140	0.0143
	500.0	0.0167	0.0174	0.0163	0.0170
	1000.0	0.0198	0.0200	0.0185	0.0187
126^o	1.0	0.0151	N.T.	0.0151	
	10.0	0.0111	N.T.	0.0111	
	50.0	0.0119	N.T.	0.0119	
	100.0	0.0129	N.T.	0.0129	
	200.0	0.0144	N.T.	0.0144	
	500.0	0.0170	N.T.	0.0166	
	1000.0	0.0203	N.T.	0.0190	

N.T. - Not tested
All measurements at 1.0 VRMS

Table 29: Dissipation Factors for the Araldite CY9729 - Polymat Transformer HV Insulation System as a Function of Frequency and Temperature - Both measured and Corrected Values

Temp	Freq.	D.F. Measured		D.F. - Corrected	
(^{o}C)	(KHz)	5 - 1	5 - 2	5 - 1	5 - 2
26^{o}	1.0	0.0059	0.0059	0.0059	0.0059
	10.0	0.0106	0.0106	0.0106	0.0106
	50.0	0.0134	0.0133	0.0134	0.0133
	100.0	0.0143	0.0142	0.0143	0.0142
	200.0	0.0153	0.0152	0.0153	0.0152
	500.0	0.0168	0.0166	0.0164	0.0162
	1000.0	0.0182	0.0180	0.0169	0.0167
64^{o}	1.0	0.0065	0.0065	0.0065	0.0065
	10.0	0.0092	0.0092	0.0092	0.0092
	50.0	0.0122	0.0121	0.0122	0.0121
	100.0	0.0136	0.0135	0.0136	0.0135
	200.0	0.0151	0.0150	0.0151	0.0150
	500.0	0.0176	0.0174	0.0172	0.0170
	1000.0	0.0200	0.0197	0.0187	0.0184
85^{o}	1.0	0.0112	0.0114	0.0112	0.0114
	10.0	0.0116	0.0118	0.0116	0.0118
	50.0	0.0132	0.0134	0.0132	0.0134
	100.0	0.0143	0.0144	0.0143	0.0144
	200.0	0.0157	0.0157	0.0157	0.0157
	500.0	0.0181	0.0181	0.0177	0.0177
	1000.0	0.0206	0.0204	0.0193	0.0191
106^{o}	1.0	0.0238	0.0243	0.0238	0.0243
	10.0	0.0204	0.0207	0.0204	0.0207
	50.0	0.0193	0.0196	0.0193	0.0196
	100.0	0.0193	0.0202	0.0193	0.0196
	200.0	0.0200	0.0202	0.0200	0.0202
	500.0	0.0212	0.0217	0.0212	0.0213
	1000.0	0.0236	0.0236	0.0236	0.0223
126^{o}	1.0	0.0334	N.T.	0.0344	
	10.0	0.0315	N.T.	0.0315	
	50.0	0.0292	N.T.	0.0292	
	100.0	0.0283	N.T.	0.0283	
	200.0	0.0279	N.T.	0.0279	
	500.0	0.0279	N.T.	0.0275	
	1000.0	0.0296	N.T.	0.0283	

N.T. - Not tested
All measurements at 1.0 VRMS

Table 30: Dissipation Factors for the Scotchcast MR283/U000- Polymat Transformer HV Insulation System as a Function of Frequency and Temperature - Both measured and Corrected Values

percent. It should be noted that none of the DF variations should be attributed to moisture effects since all MTSs used in these evaluations maintained at less than 10 percent relative humidity from the completion of the post - cure until the DF tests were performed.

B2 Summary.

This activity has demonstrated an effective method for evaluating the AC loss characteristics of an electrical insulation system over a range of temperatures and frequencies. Included were methods for determining the AC loss characteristics of the of the measurement system including the use of "standards" and the development of correction factors to compensate for losses caused by the system. "Standards" can be any device and fixturing whose AC loss characteristics are accurately known over the range of test conditions. In these evaluations, the "standards" were the HP test fixture (Model 16047A) and the variable air capacitor. Without the use of such "standards" and the resulting correction factors, if occurring, any variations in the measured value cannot be precisely assigned to the MTS or device being tested. For these evaluation only the correction factors associated with the test frequencies were considered consequential and were used.

The DF determinations for the four transformer HV insulation systems has shown the variations in AC losses occurring as a function of temperature and frequency. Each of the four HV insulation systems demonstrates typically, unique AC loss characteristics over the range of test conditions. The results show variations between materials under the same conditions exceeding 400 percent, e.g., Epon 825/HV vs. MR 283/U000 at 1.0 kHz and 106°C with the Epon system having the lower loss. For a material, the AC loss also varies with conditions. Typically the losses increase with frequency the exception being values occurring at or near resonant frequencies. Temperature effects can result in the losses either increasing or decreasing with increasing temperatures depending on the construction materials. These variations can be seen by reviewing the resulting AC losses for each of the four insulation systems.

It is important when selecting or evaluating HV insulations to establish their AC loss characteristics at the operating frequencies and over the temperature range of use, particularly at room-temperature or the operating temperature and the maximum exposure temperature. The use of room-temperature values exclusively can result in loss predictions which can be in error by several hundred percent and with potentially damaging or catastrophic effects.

C. High Voltage Characterizations.

The High Voltage Characterizations of the four transformer HV insulation systems involved the following activities:

- o AC and DC corona characterizations.
- o modified DC dielectric withstanding voltage determinations.
- o thermal stress effects.

- o life tests.
- o voltage breakdown determinations
- o electrical resistivity determinations.

The test sequence used in these evaluations is shown in Figure 3.

In the Introduction, four objectives were identified to direct the evaluation of the four electrical insulation materials for use as possible transformer HV insulation systems. Two of the objectives were

- o evaluation of various electrical insulation combinations as HV insulations for transformers
- o determination of thermal stress effects on the behavior of the insulation systems.

The six activities described above were undertaken to satisfy these objectives.

The probable effectiveness of any electrical insulation system as a HV isolator can be established through a combined series of evaluations involving corona characterizations, withstanding voltage determinations, thermal stress responses, HV life testing, and voltage breakdown determinations. Depending on the design and the construction, mechanical stressing and analyses may also be required as part of the evaluation.

Corona characterizations are probably the most reliable predictor of an insulation systems integrity and performance. This results because the processes which produce corona are the same ones which cause electrical breakdown and insulation failure. A complete corona characterization would include the determination of Inception and Extinction voltages (commonly referred to as CIV and CEV) under both AC and DC conditions. The measurement of the charge transfer associated with the corona process would also be a part of these characterizations. These measurements are usually referred to Discharge Energy determinations even though the measurement is only one of charge transfer and not energy. The AC determinations may serve two functions

- o to assess the performance when the insulation will be used under AC voltages. In this circumstance, it is best to make the measurements at the operating frequency. When it is not possible, then the measurements can be made at a testable frequency such as 60 Hz and the results extrapolated to the operating frequency. Such extrapolations are usually valid from low frequencies such 60 HZ to approximately 100 kHz plus. At higher frequencies, additional dielectric processes can make these extrapolations unreliable.
- o to determine the general quality of an insulation material or system. AC corona measurements are usually quicker to perform than are DC measurements. While yielding different results than DC, AC values can be correlated with DC requirements and may be used as screening tests for products to be used in DC environments.

When the insulation system is to operate under DC conditions, the evaluation of the system should include DC corona testing. DC tests are typically more time consuming than AC measurements. This is due in part to the fact that DC testing is most effectively done in a stepped voltage manner requiring a time interval at each step to monitor for corona whereas the AC measurement can be made under a continuos rate of voltage increase. When a stepped increase is used with AC the hold intervals can be less since if corona is present it will occur on each half or full cycle. Unless the DC corona levels are significant at inception or the required test voltage, the observation period should be several or several 10's of seconds to accurately evaluate the product behavior at the step condition. This requirement exists because of the nature of low level DC corona discharge in which the discharge process usually occurs in a non-periodic but recurrent manner. DC corona determinations under usage voltages are probably the best indicator of the insulation system integrity and the capability to meet the operating life time requirements. Such determinations to be most effective should include "discharge energy" measurements. Finally, when AC corona determinations are to be used as a quality indicator where the insulation will be used under DC voltages, correlation tests between the AC and DC corona responses must be made.

Dielectric Withstanding Voltage (DWV) determinations can be used to establish an insulation systems capability to support or not a pre-defined voltage, generally for a short period of time. Such a test is useful to identify systems which would fail immediately at the pre-defined voltage. In these evaluations, the "modified DWV" included a leakage current monitor which was used to determine the leakage current at the test voltage. The addition of this measurement can identify insulation systems which may be faulty but which pass the DWV test, i.e., do not fail catastrophically. The usual DWV test is a pass/fail test in which the product either fails catastrophically or not with no other indication of the quality.

Next to the actual high voltage behavior of an insulation system, the thermal stress response is probably the most significant indicator of the operational integrity for a candidate system. In fact, it is the resultant high voltage behavior during and after thermal stressing that provides the best indication of a insulation systems suitability for an intended application. Thermal stressing usually is present in one of two conditions, thermal shock or thermal cycling; frequently both are present or are required to be used in the evaluations of candidates. The principal difference between the two is the rate of temperature change, although at times the two conditions will employ different temperature conditions. Usually the higher rate of temperature change will result in greater thermomechanical stressing of the system, and is therefore more likely to produce mechanical damage leading to high voltage problems. Hence, thermal shock is generally the more rigorous test and is used as a screening test for candidates. In some instances, thermal shock tests are used exclusively to assess a products applicability and quality.

It should be noted that no mention has been made of mechanical testing of candidate transformer HV insulation systems. In most designs and constructions, and the resultant applications, the stresses due to mechanical loading are a fraction of those produced thermomechanically. Hence, if a system can meet the thermal stress requirements it will be suitable mechanically. While this is generally true, the mechanical loading should always be reviewed to assure the validity of the use of thermomechanical testing as the most effective screening test. This relationship is usually applicable to electronic transformer HV insulation systems. These insulations systems are generally an monolithic structure combining windings, shields, heat transfer hardware, and the electrical insulations. Such systems usually operate at frequencies greater than power-line with the average power levels of less than 10 kW. For electrical transformers, operating at the lower frequencies and higher power levels, mechanical assessment of the insulation can become as or more important than the thermomechanical responses. This occurs because the construction of these transformer types frequently employ mechanical assembly and supports. Whenever any design employs either mechanical assembly and/or supports, mechanical analyses and testing should be included in the evaluation.

Life testing of HV insulation systems can be performed in a variety of modes and conditions. The key considerations when selecting a format for life testing are to include stress conditions - electrical, thermal and as appropriate mechanical and environmental - corresponding to or multiples of those present in the application requirements. Where there are no specific requirements, as is the case in these evaluations, the test conditions should be consistent for each comparative test with the conditions chosen to reflect potential applications or composites of applications. Life testing can be performed in real-time or in an accelerated form. In real-time testing, tests are performed under actual operating conditions, such as voltages, temperatures, times, and other relevant stress and operating environments. The resulting responses are then direct time related. For accelerated tests, one or more of the operating conditions is exaggerated, i.e., is some multiple of the operating value. When accelerated conditions are used, it is not always easy to identify the appropriate multipliers to be applied to predict life-times under actual operating conditions. This results because most of the wear-out and failure causing processes which are present due not have well defined, or even known, reaction rates. The most common practices are to apply Arrehenius rate relations to all or most of the accelerated factors. While this yields an approximation, the resulting value can be in question. Where more precision is necessary, the acceleration factors are best determined by performing parallel real-time tests and comparing the times - to - failure. A high degree of variability in the extrapolated life-times can be experienced when using accelerated voltages. In some instances the variations in acceleration factors can exceed 1000 times or more. Such variations can make predictions based on accelerated conditions of marginal value. In all instances of accelerated testing, care should be taken not to introduce processes or mechanisms of wear-out and failure which do not exist under normal or non-accelerated operating conditions. The introduction of such processes renders the accelerated test invalid for predictive purposes. In general, the use of accelerated test results should be considered and used advisedly.

The Electrical Breakdown Voltage, or Dielectric Strength, provides an indicator of the maximum voltage required to cause immediate failure of an insulation system. This test may be performed on a system, sub-assembly, etc. or on material samples. When performed on systems etc., this test is useful in identifying systems whose designs are below the specified operating levels and as an approximate indicator of the margin of over stress a design may be capable of supporting. Caution should be taken when assessing the margin of over stress and relating these margins to life-times for the insulation. As noted previously, the life-times of HV insulation systems are influenced and promoted by multiple factors. In most electrical breakdown tests, many of these factors are not part of the test environment. The absence of these other factors significantly limits the validity of the use of the marginal values for life-time predictions. When this test is applied to materials for the purpose of comparison, each of the materials must be tested under the same conditions. In particular the electrode geometries and spacings must be the same. Any variations render comparisons of questionable value.

The electrical resistivity of insulation systems is included in the High Voltage Characterizations because in HV applications variations in insulation resistances will result in voltage divisions in relation to these variations. Such voltage variations can result in overstressing an insulation leading to immediate or premature failure. For this reason it is important to know the resistivities of candidate and proposed insulation systems when more than one material may be used. It is desirable to know the resistivities over the operating temperature range. Where it is not possible or practical to develop this information, then, room-temperature and the maximum operating values should be obtained. It should be noted that this resistivity information applies to DC applications, which are the conditions most frequently encountered. When HVAC conditions are present, then, the dielectric constant values of the insulation products are required to establish the voltage distributions.

C1 High Voltage Characterization Tests and Results.

Because of the integral nature of the HV characterization process used to evaluate the four HV insulation systems, the tests used in these evaluations and the results are presented in an integrated form. First the procedures for the various tests are described, and then the combined results for each of the HV insulations are summarized.

C1.1 Electrical Resistivity Measurements.

The electrical resistivities were determined on one sample for each of the four MTS types. These determinations were made at room-temperature, 22° - 26°C, and 125°C. The measurement method utilized a current-voltage procedure. Here, 100 VDC was applied to the MTS and the resulting current recorded after 2.0 minutes of electrification. For the elevated temperature tests the MTS was held at temperature for a minimum of 20 minutes before testing; this was to allow the sample to achieve thermal equilibrium before testing. The power source used was a Keithley Model 247 and the current monitor was a Keithley Electrometer, Model 617. The test chamber was isolated from the MTS and grounded and all connecting cables were triaxial with Teflon insulation.

The electrical resistivities were determined as follows:

$$R\{V\} = (V)(A) / (I)(t)$$

where R{V} is the volume resistivity, V the test voltage, A the electrode area, I the current, and t the spacing between electrodes. For the four MTS types, the electrode areas were:

$$A = 3.1416\ (D)(L)$$

where D is the MTS diameter at the mid-point between the two windings and L the winding length. These values were 0.825 and 1.38 inches respectively. The area was 3.58 sq. inches. The electrode spacing, t, was 0.003 inches. The cell constant, k:

$$k = A / t$$

for the MTSs was 1192. inch or 3028. centimeter.

C1.2 Corona Characterizations.

The corona characterizations included both AC and DC determinations. The sequence followed in these evaluations is shown in Figure 3. Determinations were performed before and after post-curing , before and after thermal shock, and before and after life-testing. MTSs

Following are descriptions of the conditions, equipment, procedures and results used in the corona determinations. All determinations were made with the MTS's completely immersed in Freon TF at room-temperature, 22° - 26°C. Both the AC and the DC measurements were made using a Biddle Corona Test System with a Hughes designed corona detector and pulse counter. The AC HV power supply was rated at 60 kV and 10. mA.. The DC supply was rated at 75 kV and 5. mA.. The Hughes corona detector was an eight channel analyzer with a resolution limit of 0.2 picocoulombs. Each of the eight channels could be programmed to count corona pulses from 0.2 to 10,000. picocoulombs. Typically the analyzer would be set-up to count pulses the 1.0, 5.0, 10., 25., 50., 100., 500., and 1000. picocoulomb levels. These levels could be varied if observations suggested other counting profiles. The total counts could be summed to determine the total discharge charge when a requirement existed for a "discharge energy determination".

Prior to the testing of the MTS's, the test system was tested to establish its corona inception level. The test system included all of test apparatus excluding the MTS - the power supply, the detector and counter, interconnections, HV test leads, and test vessel containing the Freon TF. For both the AC and DC tests, the system was required to be corona-free at 1.5 times the maximum voltage to be used during the MST testing. Corona-free in these tests was defined as no discharges of 0.2 picocoulombs or greater occurring at the 1.5 times voltage level.

For the AC determinations, the MTS was immersed in the Freon TF and observations were made for both the corona inception voltage (CIV) and the corona extinction voltage (CEV). In these tests, the voltage was increased at a continuos rate until the CIV was detected. The voltage was then decreased until the CEV was noted. In these tests, the CIV was defined as the voltage producing a discharge of 1.0 picocoulombs or greater and the CEV the voltage at which the discharge became less than 1.0 picocoulomb once a discharge was present. Following the AC corona determinations prior to post-curing, the AC voltage was limited to 6.0 kVRMS, which would produce an average electrical stress of 2000 volts per mil. The pre-post cure measurements resulted in several electrical breakdown failures at voltage levels substantially above 6.0 kV. These higher test levels were considered to provide information of negligible value in terms of determining degradation processes and to put the MTS's at greater risk of catastrophic failure thus eliminating their intended use in other tests.

The DC determinations were determined used a stepped increase in voltage procedure. With the MTS completely immersed in Freon TF, the voltage was increased to a predetermined level, then monitoring for corona for a prescribed period. If no discharges were observed, the voltage was again increased and monitored for the specified period. This process was repeated until corona was detected (CIV). No CEV determinations were made. As with the AC determinations, corona inception was defined the voltage producing a discharge of 1.0 picocoulomb or greater. The step increased used were 1.0 kV and the monitored periods were 30 seconds. The maximum voltage used in these tests was 8.0 kV. This voltage resulted in average electrical stresses of 2667. volts per mil. This limit was imposed to minimize the likelihood of electrical breakdown of the MTS, since this was not the objective of these tests and most of the samples were to be used in other tests.

C1.3 Dielectric Withstanding Voltage Tests.

The Dielectric Withstanding Voltage tests were all performed using DC voltages with the MTS's immersed in Freon TF at room-temperature, 22- 26°C. The test voltage was 8.0 kV and the electrification time was 60 seconds. Included as part of the test was the monitoring of the associated leakage current. In these determinations, those MTS's which did not fail catastrophically or whose leakage current at 60 seconds did not exceed 50 nanoamperes were determined to PASS the test. Devices which exceeded the 50 nanoampere level were so noted but were continued in the test series.

C1.4 Thermal Shock Tests.

The Thermal Shock conditions used in these evaluations are presented in Table 31. The test chamber was a Tenney vertical 2 - chamber design. For these tests a nitrogen purge was used to prevent the presence of condensation on the MTS's.

Parameter	Value
Temperature Range	-55^oC to $+130^oC$
Transfer Time	< 15 seconds
Dwell at Temperature extremes	0.5 hours
No. of cycles	24*

* - 25 cycles were planned, but the last cycle not performed due to a refrigeration compressor problem with the thermal shock chamber.

Table 31: Thermal Shock Conditions for the Evaluation of the Transformer HV Insulation MTS's

C1.5 Life Tests.

The Life tests were performed at 8.0 KVDC under room-ambient conditions. A diagram of the test circuit is shown in Figure 10. The DC power supply was a Spellman Model RHR PN60, rated at 60 kV and 2. mA. The current limit - failure monitoring resistors were comprised of five 10 megohm, 2 watt resistors and one 1 megohm, 2 watt resistor in series with each of the MTS's under test. The 1 megohm resistor served as the failure monitor. The duration of the life tests was approximately 1100 hours with failure monitoring every 24 hours.

C1.6 Electrical Breakdown Tests.

The Electrical Breakdown or Dielectric Strength tests were performed using DC voltages with the MTS's immersed in Freon TF at room-temperature, 22° - 26°C. For these tests the voltage was increased at a continuous rate until electrical breakdown occurred; the nominal rate of increase was 100 to 300 volts per second. For these tests, the Biddle system was used. A 5 megohm, 20 KV resistor and a 20 KV diode were placed in series with the MTS under test to limit the current present in the HV circuit to less than 5. mA and to eliminate oscillation voltages. This was done to protect the HV circuit of the Biddle system.

C1.7 Results.

The HV characterizations for each of the four transformer HV insulation systems are summarized in the following sections.

Epon 825/HV - Polymat. (see Tables 32, 33 and 43 and Figures 11, 12 and 19.).

It should be noted that all of the Epon 825/HV - polymat MTS's used in these evaluations had cracks. The cracks varied in size and location and resulted from an insufficient amount of polymat wrap over the outer winding. Instead of several layers of polymat, sufficient to result in a polymat "build" equal to the mold inside diameter, a single or two layer wrap was used. This produced a "resin-rich" layer on the exterior of the MTS's. This layer was the initiation region for the cracks which occurred during the removal from the initial casting molds, and subsequently during post-curing and thermal shock. The crack locations varied but each of the MTS's was observed to have cracks extending into the winding area. Normally such conditions would have resulted in discarding these devices and refabricating units for evaluation. This was not done here for two reasons. First, the cost and schedule constraints of the program did not favor this approach. Second, the use of "flawed" MTS's was considered likely to yield failures during a reasonable period of life test time which would in turn permit the demonstration of corona-to-life time relationships. The results described below are for the flawed MTS's.

AC corona. The AC corona levels were generally unchanged following the initial cure through thermal shock. This observation is made even though the corona test levels were changed after the initial cure where each MTS was tested to its CIV level. After the initial cure, the maximum voltage was limited to 6.0 KV. Devices whose CIVs were below 6.0 KV after the initial cure were essentially unchanged subsequently. Those MTS's whose CIVs were above 6.0 KV after the

AC CORONA - KVAC								
MTS SERIAL NUMBER	Before Post Cure		After Post Cure*		After Thermal Shock*		After Life Test*	
	CIV	CEV	CIV	CEV	CIV	CEV	CIV	CEV
5 - 1	5.5	5.0	5.4	4.7	5.3	4.4	L.F.	
5 - 2	3.0	1.1	3.7	1.6	4.3	1.3	L.F.	
5 - 3	2.4	1.4	3.2	1.5	2.6	0.9	L.F.	
5 - 4	8.9	7.7	>6.0	>6.0	>6.0	>6.0	N.T.	
5 - 5	8.8	5.9	>6.0	>6.0	6.0	6.0	L.F	
5 - 6	5.5	2.8	3.6	3.1	3.1	1.3	N.T.	
5 - 7	9.4	8.7	>6.0	>6.0	>6.0	>6.0	N.T.	
5 - 8	8.1	4.1	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0
5 - 9	6.9	6.1	>6.0	>6.0	6.0	6.0	L.F.	
5 - 10	7.3	5.5	N.T.		N.T.		N.T.	
Avg.	6.6	4.8	>5.1	>4.5	>5.0	>4.2		
Std. Dev.	2.3	2.4	>1.2	>1.8	>1.3	>2.1		

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
* - 6.0 KVAC RMS max. test voltage

Table 32: AC Corona Characteristics for the EPON 825/HV - Polymat MTS HV Insulation Systems

DC CORONA - KVDC							DC DWV at 8.0 KV	
MTS SERIAL NUMBER	After Post Cure*		After Thermal Shock*		After Life Test*		After Post Cure	After Thermal Shock
	CIV**	PC	CIV**	PC	CIV**	PC	Results	Results
5-1	8.0	0	8.0	0	L.F.		Pass	Pass
5-2	8.0	0	8.0	0	L.F.		Pass	Pass
5-3	8.0	0	8.0	0	L.F.		Pass	Pass
5-4	8.0	0	8.0	0	N.T.		Pass	Pass
5-5	8.0	0	8.0	0	L.F.		Pass	Pass
5-6	8.0	0	8.0	0	N.T.		Pass	Pass
5-7	8.0	0	8.0	0	N.T.		Pass	Pass
5-8	8.0	0	8.0	0	8.0	0 (0)	Pass	Pass
5-9	8.0	0	8.0	0	L.F.		Pass	Pass
5-10	8.0	0	N.T.	0	N.T.		Pass	Pass
							Pass	N.T.

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
* - 8.0 KVDC max. test voltage
** - If pC=D, CIV assumed greater than 8.0KV
( ) - 10 minutes value after life test

Table 33: DC High Voltage Characteristics for the EPON 825/HV - Polymat HV Insulation Systems

initial cure remained above 6.0 KV through subsequent processing and tests.

The CIV levels ranged from 2.4 kVAC for Serial Number 5-3 to 9.4 kVAC for Serial Number 5-7 after the initial cure. The CEV values ranged from 0.9 KVAC for Serial Number 5-3 after thermal shock to greater than 6.0 KVAC for Serial Numbers 5-4,-7, and -8 after the initial cure and following thermal shock. Serial Number 5-8 produced CIV and CEV values of greater than 6.0 KVAC after 1100 hours of life tests. The average CIVs for these MTS's were 6.6 kVAC after the initial cure and greater than 5.1 and 5.0 kVAC after post-cure and thermal shock. The greater than values result from the use of the greater than 6.0 kV values in determining the average values.

The results of the AC corona tests are given in Table 32.

DC corona. All of the MTS's showed no change in DC corona levels after the initial cure through thermal shock. None of the devices exhibited any detectable corona at 8.0 KVDC during the 30 second test period, the maximum voltage and interval used in these tests. Serial Number 5-8, after 1100 hours of life tests, yielded no detectable discharge current when tested at 8.0 KV for 10 minutes. This was similar to the 30 second results before the life tests.

Since none of the life test MTS's exhibited any corona before life tests yet all but one failed during the 1100 hour test period, it is apparent that the monitoring period of 30 seconds was insufficient to detect the corona that must be present for the life test failures. It is also possible that the corona measurements in Freon TF eliminated corona which was present during the life tests which were conducted in air. Because of the low surface tension of Freon cracks may have been filled during the tests in the liquid thus eliminating corona in these tests. When life tested in air the cracks containing only air could now produce the discharge process.

The results of the DC corona tests are presented in Table 33.

Modified Dielectric Withstanding Voltage. All of the MTS's passed the modified DWV tests which were performed after the post-cure and the thermal shock tests. None of the devices produced leakage currents approaching the limit value of 50 nanoamperes.

The DWV test results are given in Table 33.

Thermal Shock. As noted above all of the MTS's exhibited some cracking after the initial cure. While no attempt was made to physically map these cracks, the general observation was that the cracks increased and some additional ones formed during the thermal shock tests.

The HV responses resulting from these tests have been discussed above and summarized in the referenced Tables.

Life-Time Tests. The life-times at 8.0 KVDC at room-temperature in air ranged from 24 hours for Serial Number 5-3 to in excess of 1100 hours for Serial Number 5-8. Serial Number 5-8 had not failed when the test was terminated at 1116 hours. The average time-to-failure for the six MTS's tested was greater than 469 hours, the longest of the four HV insulation systems tested. A summary of the life-times for the Epon 825/HV - polymat system is given in Figure 19.

The relationships between the corona characteristics and the life-times for the MTS's are presented in Figures 11. and 12. Figure 11. shows a significant correlation between the AC corona inception levels and the life-times of the MTS's. The MTS with the lowest CIV produced the shortest life-time (Serial Number 5-3), while the longest life-time occurred with the MTS having the highest CIV (Serial Number 5-8). This correlation was not observed with DC corona tests; see Figure 12. Reasons for the absence of correlations for the DC corona responses have been discussed above.

For illustration purposes, using the life-times produced in these tests, life-times at other electric field strengths can be determined by the following relationship:

$$L(1) = \{L(2)\text{POWER}\,\{V(2)/V(1)\}\}/N \qquad (1).$$

where L(1) is the life-time at V(1), L(2) is the life-time at V(2) and N is an integer which is experimentally determined, usually between 1 and 10. Either the voltages, V, or the electric field strengths may be used in these determinations. Using the average life-time of 467 hours for these MTS's at 8.0 KV, the calculated life-time at 4.0 KV would be 218,000 hours for a value of N = 1.

Again, it should be noted that the life-times resulting in these tests were for flawed MTS's; the values are not reflective of those which would result had MTS's without these obvious flaws been tested.

Electrical Breakdown Voltages. No electrical breakdown voltage determinations were made for the Epon 825/HV insulation system.

Electrical Resistivities. The electrical resistivities for the Epon 825/HV - polymat insulation system at room-temperature and 125°C are given in Table 43.

Araldite CY9729 - Polymat. (see Tables 34 - 36, and 43. Figures 13, 14 and 19.). As with the Epon 825/HV - polymat samples, all of the Araldite CY 9729,... MTS's had cracks and for the same reasons. Again, an insufficient amount of polymat wrapping had been applied

Transformer HV Insulation Systems

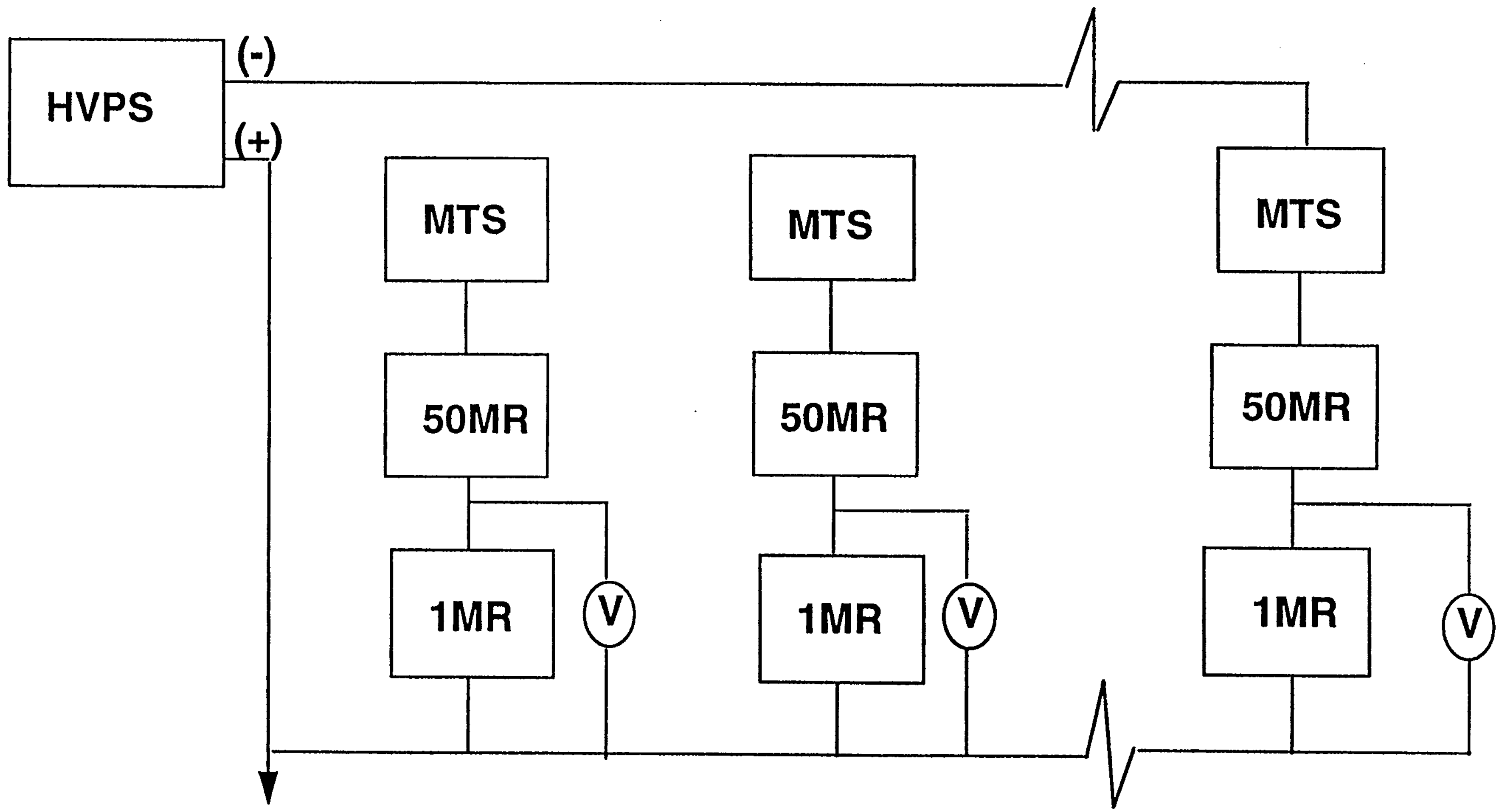


Figure 10

Life Test Circuit Configuration for the Transformer HV Insulation Systems MTS's

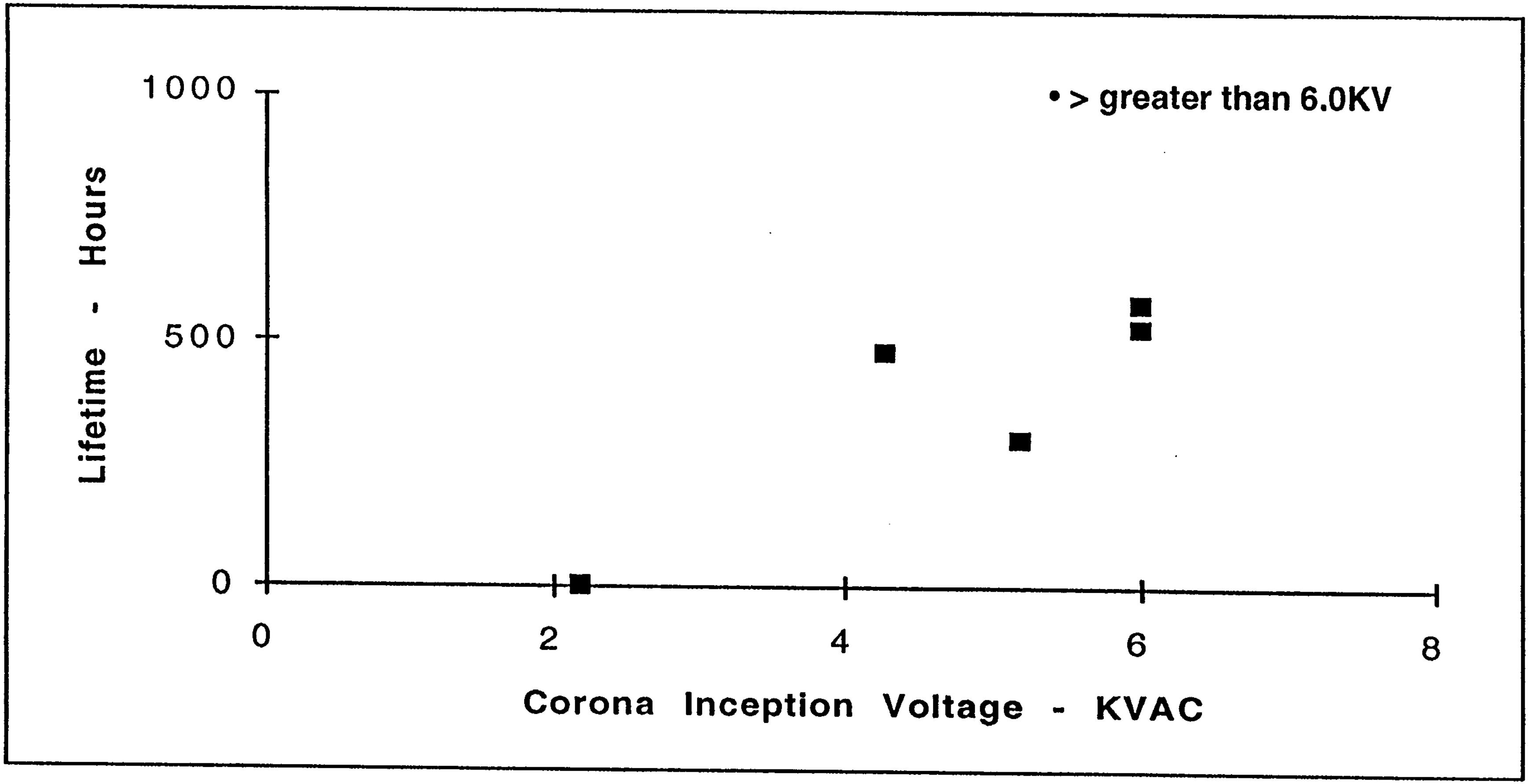


Figure 11

Relationships Between MTS Lifetimes and Corona AC Inception Voltages for EPON 825/HV - Polymat HV Insulation Systems

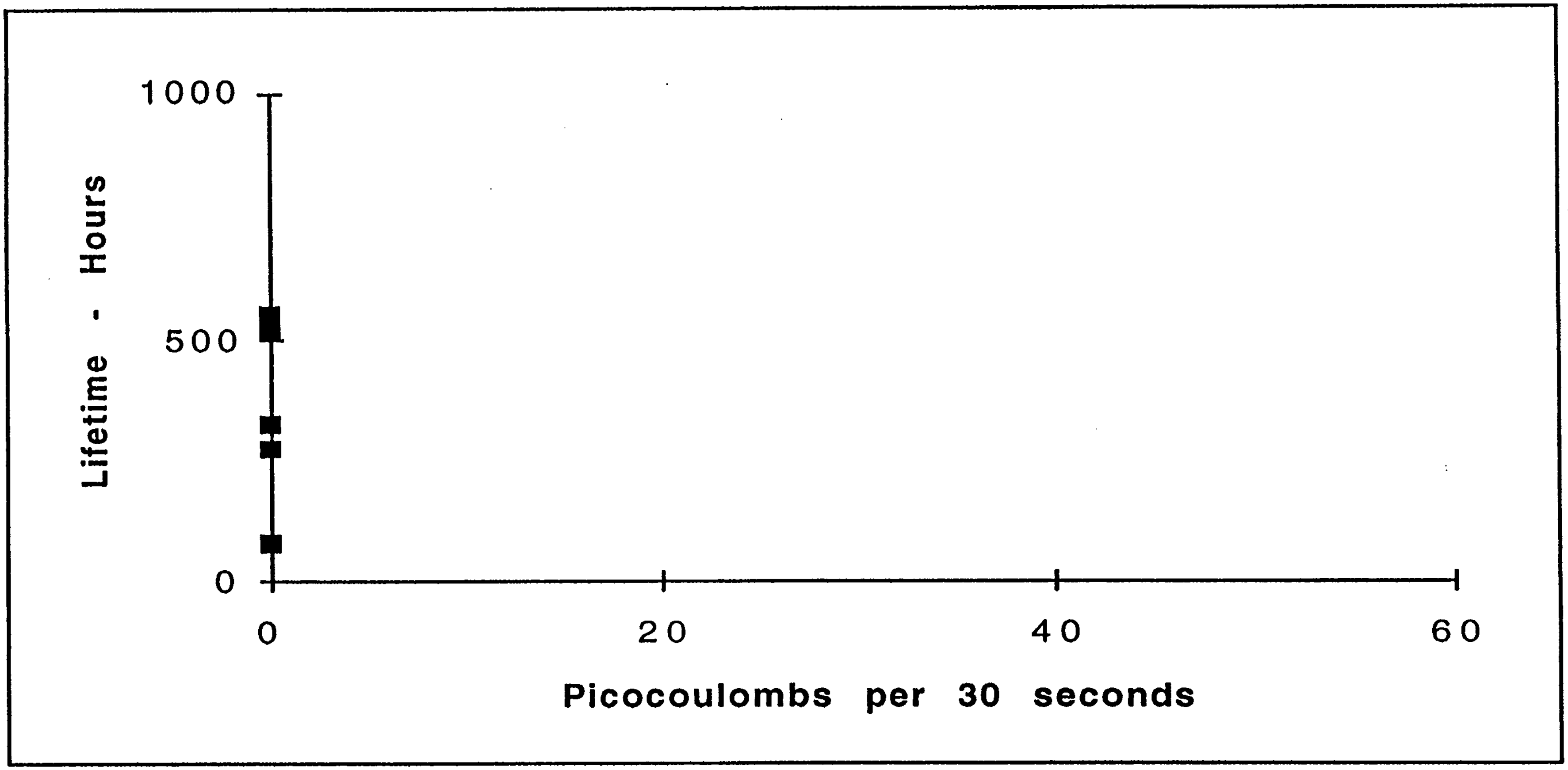


Figure 12

Relationship Between DC Corona Discharge Levels and MTS Lifetimes at 8.0KV for EPON 825/HV Polymat HV Insultation Systems

AC CORONA - KVAC								
MTS SERIAL NUMBER	Before Post Cure		After Post Cure*		After Thermal Shock*		After Life Test*	
	CIV	CEV	CIV	CEV	CIV	CEV	CIV	CEV
7-1	6.3	5.4	7.0	5.8	N.T.			
7-2	5.1	4.3	7.2	5.4	>6.0	>6.0	L.F.	
7-3	7.0	6.3	6.5 (VBD)					
7-4	9.3(VBD)							
7-5	3.8	1.3	3.9	1.6	5.9	1.3	L.F.	
7-6	8.0	6.2	6.3	5.5	>6.0	>6.0	L.F.	
7-7	5.7	2.4	7.3(VBD)					
7-8	9.4	4.1	8.0 (VBD)					
7-9	8.8	7.7	7.8	2.8	6.0	6.0	L.F.	
7-10	6.3	2.0	7.4 (VBD)					
Avg.	7.0	4.5	6.8	4.2	>6.0	>6.0	>4.8	
Std. Dev.	2.1	2.1	1.2	1.3	>0.05	>2.0	-	

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
* - 6.0 KVAC RMS max. test voltage
VBD - voltage breakdown

Table 34 AC Corona Characteristics for the Araldite CY9729 - Polymat HV Insulation System

DC CORONA - KVDC							DC DWV at 8.0 KV	
MTS SERIAL NUMBER	After Post Cure*		After Thermal Shock*		After Life Test*		After Post Cure	After Thermal Shock
	CIV**	PC	CIV**	PC	CIV**	PC	Results	Results
7-1	N.T.							
7-2	8.0	0	8.0		L.F.		Pass	Pass
7-3	P.F.							
7-4	P.F.							
7-5	8.0	0	8.0		L.F.		Pass	Pass
7-6	8.0	0	8.0		L.F.		Pass	Pass
7-7	P.F.							
7-8	P.F.							
7-9	8.0	0	8.0		L.F.			
7-10	P.F							

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
P.F. - Previous failure
* - 8.0 KV max. test voltage
** - if pC = 0, then CIV assumed greater than 8.0KV

Table 35: DC High Voltage Characteristics for the Araldite CY9729 - Polymat HV Insulation System

MTS Serial Number	AC Breakdown Voltage (KVAC)	DC Equivalent Voltage (KVDC)	Electrical Stress - DC Equivalent (Volts/Mil)
7-3	6.5	9.2	3067.
7-4	9.3	13.1	4367.
7-7	7.3	10.3	3433.
7-8	8.0	11.3	3767.
7-10	7.4	10.4	3467.
AV.	7.7	10.9	3633.

Table 36: AC Electrical Breakdown Voltages and the Associated DC Equivalent and Values for the Araldite CY9729 - Polymat HV Insulation Systems

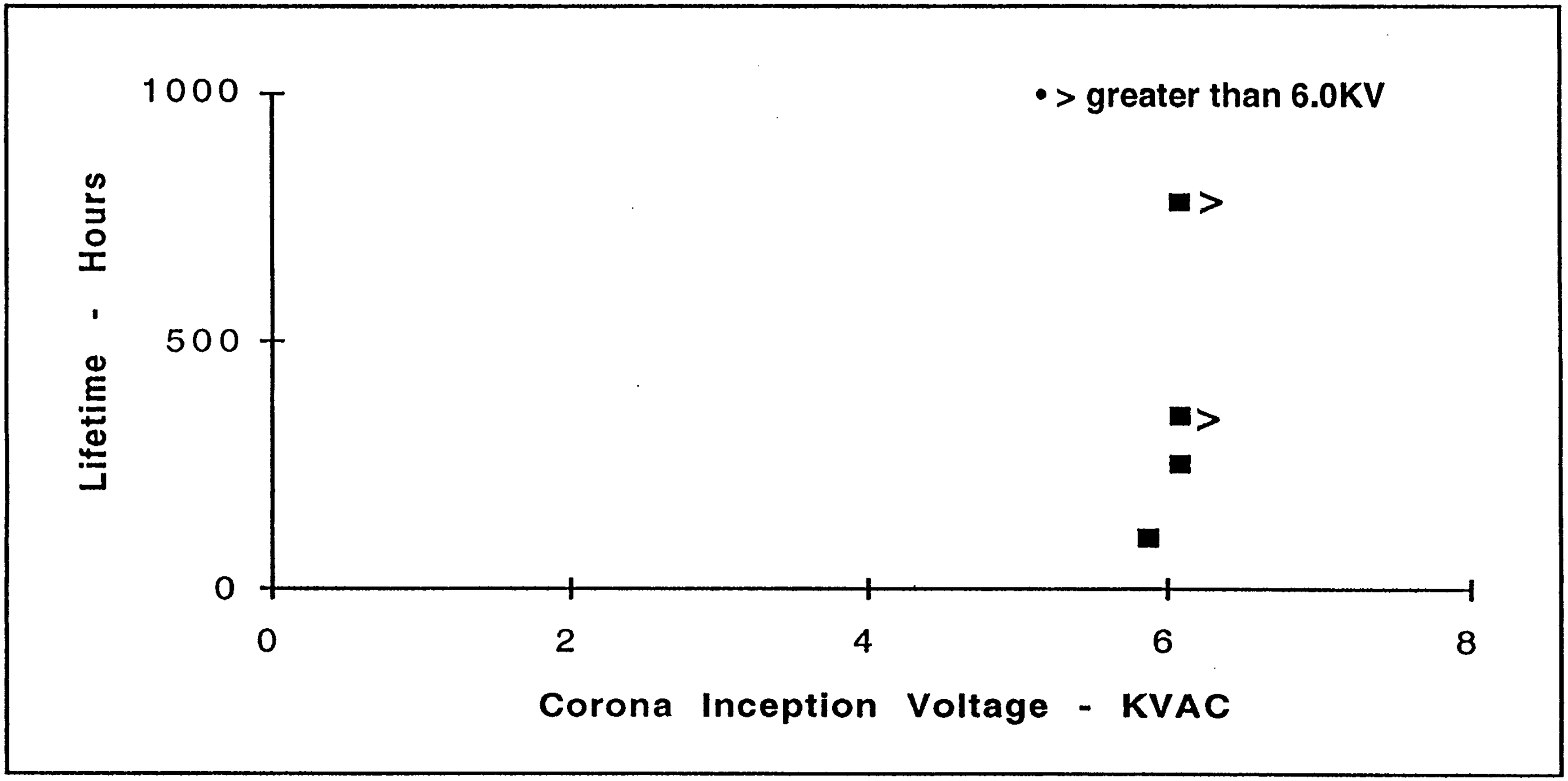


Figure 13

Relationships Between MTS Lifetimes and Corona AC Inception Voltages for Aradite CY9729 - Polymat HV Insulation Systems

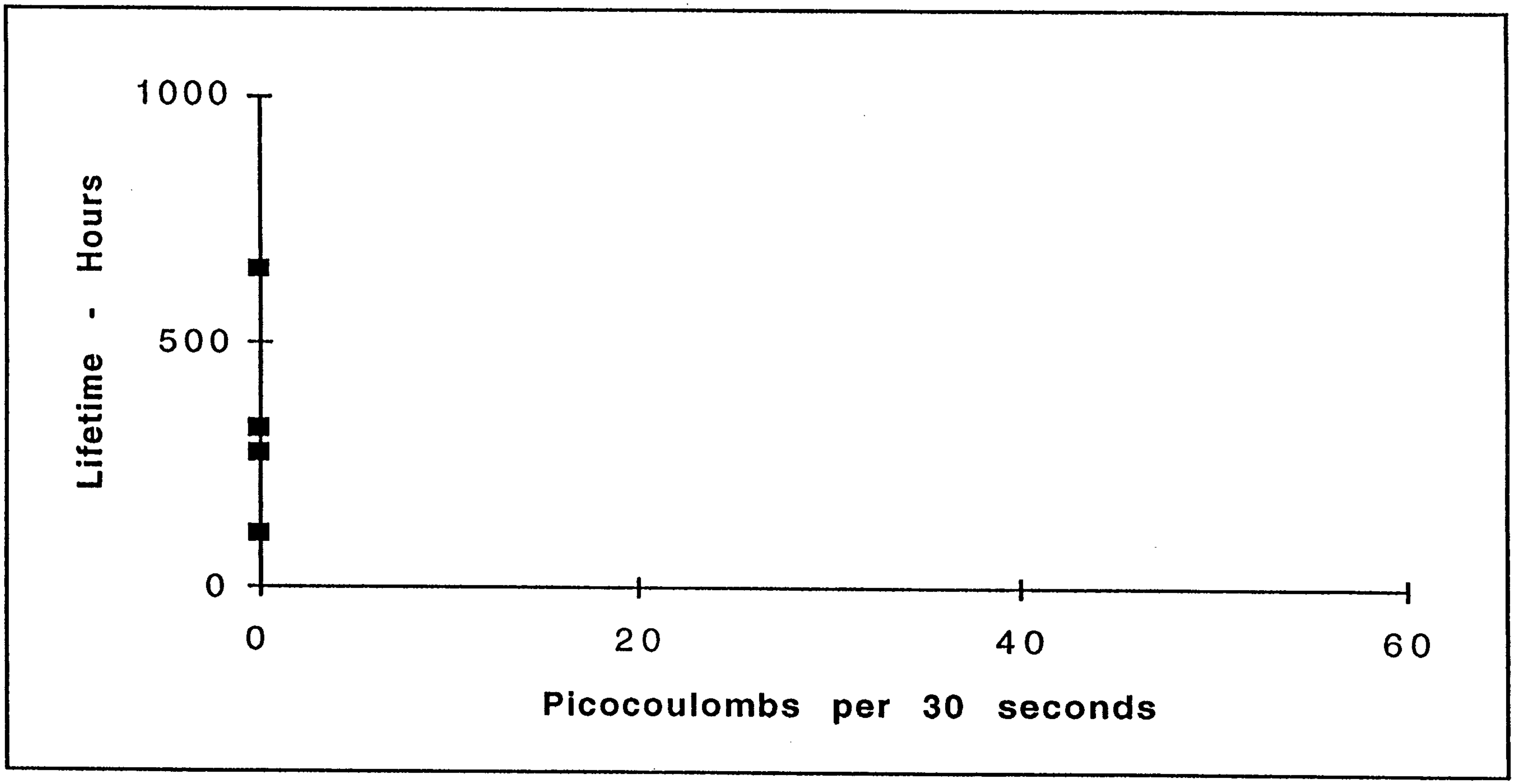


Figure 14

Relationships Between DC Corona Discharge Levles and MTS Liftimes at 8.0KV for Araldite CY9729 - Polymat HV Insulation Systems

to the outside of the MTS's resulting in a "resin-rich" layer on the outside of the test structure. For these MTS's, the cracks varied in size and location, and were observed to extend into the winding region. The results described below were developed using these MTS's.

AC Corona. The AC corona levels for these MTS's were essentially unchanged following the initial cure through thermal shock. Some devices showed some increase in the CIV in this sequence (Serial Numbers 7-2 and 7-5), while others produced reduced CIV values (Serial Numbers 7-6 and 7-9). Several samples experienced electrical breakdown during these tests resulting in limiting the test voltage to 6.0 KVAC following the thermal shock test.

The CIV values ranged from 3.8 KVAC for Serial Number 7-5 to 9.4 kVAC for Serial Number 7-8 both following the initial cure. The CEV values ranged from 1.3 KVAC for Serial Number 7-5 following both the initial cure and thermal shock to 7.8 KVAC for Serial Number 7-9 after post cure. The average CIVs for these MTS's were 7.0 KVAC after the initial cure, and 6.8 and greater than 6.0 KVAC following post cure and thermal shock.

The results of the AC corona tests for these MTS's are given in Table 34.

DC Corona. None of the MTS's produced any detectable DC corona during the measurement interval 8.0 kVDC following the initial cure through thermal shock. No DC corona tests were performed following life tests since all of these devices had failed.

The absence of measurable DC corona for these devices followed by the subsequent life test failures suggests, as it did for the Epon 825/HV system, that insufficient monitoring time was used in these determinations. It is also possible the Freon TF penetrated critical cracks eliminating DC corona which would be present under the life test conditions which were conducted in air.

The results of the DC corona tests are presented in Table 35.

Modified Dielectric Withstanding Voltage. All of the MTS's passed the modified DWV tests which were performed following post cure and thermal shock. All of the devices produced leakage currents less than the 50 nanoampere limit at the end of the 60 second electrification period.

The results of the DWV tests are shown in Table 35.

Thermal Shock. As noted all of the MTS's for this series contained some cracks following the initial cure. As with the Epon 825/HV devices, no attempt was made to map the cracks for the individual MTS's following the initial cure. General observations following thermal shock indicated the several of the original cracks had grown and that some new cracks had been formed.

The review of the HV responses resulting from the thermal shock tests have been discussed above with the results summarized in Tables 34 and 35.

Life - Time Tests. The life-times at 8.0 KVDC at room-temperature in air ranged from 116 hours for Serial Number 7-9 to 760 hours for Serial Number 7-6. The average time-to-failure was 366 hours, ranking second for the four HV insulation systems tested. A summary of the life test results for the Araldite CY 9729,...-polymat system are given in Figure 19.

The relationships between the corona characteristics and the DC life-times are shown in Figures 13 and 14. Figure 13 shows some correlation between the AC CIV and life-time with the two devices having the lowest CIVs exhibiting the shortest life-times (Serial Numbers 7-5 and 7-9). One of the two devices having a CIV greater than 6.0 KVAC yielded the longest life-time (Serial Number 7-6). The other device with the greater than 6.0 kVAC CIV (Serial Number 7-2) produced a life-time of 330 hours which was slightly less than half that of Serial Number 7-6. This was slightly greater than the life-time of 257 hours produced by the MTS with a 6.0 KVAC CIV (Serial Number 7-9). In Figure 14 no correlation is observed between the DC CIVs and the life-times of the MTS's. Possible reasons for this absence have been discussed previously in the DC Corona results.

It should be noted that all of the life-times resulting in these tests were for flawed, i.e., cracked MTS's. The results are not indicative of those which would occur for devices which did not exhibit these defects.

Electrical Breakdown Voltages. The electrical breakdown voltages for these MTS's are those produced during the AC Corona tests. These AC results were RMS values and are presented in Table 36 along with their DC equivalents.

Electrical Resistivities. The electrical resistivities for the Araldite CY 9729,...-polymat insulation system are presented in Table 43.

Ricotuff LV - Polymat (see Tables 37 - 39, and 43. Figures 15, 16 and 19.).

These MTS's like those of the preceding HV insulation systems were cracked and for the same reasons. Of the four HV insulations evaluated, the Ricotuff LV MTS's were the most extensively cracked. This is attributed to both to the lower mechanical strength of this resin system and the under cure of the material after the initial cure which yielded an even lower strength product.

AC Corona. For all devices, the AC corona levels were observed to increase following the post-cure process, and then to remain essentially

AC CORONA - KVAC								
MTS SERIAL NUMBER	Before Post Cure		After Post Cure*		After Thermal Shock*		After Life Test	
	CIV	CEV	CIV	CEV	CIV	CEV	CIV	CEV
8-1	3.7	1.9	5.2	4.3	5.9	1.8	N.T.	
8-2	2.1	1.6	2.5	2.1	2.5	1.5	L.F.	
8-3	2.1	1.6	3.1	2.2	3.5	2.2	L.F.	
8-4	2.1	1.4	2.8	1.8	2.7	1.6	L.F.	
8-5	6.0	5.3	N.T.		N.T.		N.T.	
8-6	2.4	1.5	3.8	2.2	4.0	2.1	L.F.	
8-7	2.2	1.4	2.8	1.6	2.7	1.4	L.F.	
8-8	4.4	3.5	4.5 (VBD)					
8-9	3.8	2.8	N.T.		N.T.		N.T.	
8-10	4.4	2.1	5.9	3.2	6.0	3.2	>6.0	>6.0
Avg.	3.3	2.3	3.8	2.5	3.9	2.0		
Std. Dev.	1.3	1.2	1.2	0.9	1.4	0.6		

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
* - 6.0 KVAC RMS max. test voltage
VBD - voltage breakdown

Table 37: AC Corona Characteristics for the Ricotuff LV MTS HV Insulation Systems

MTS SERIAL NUMBER	DC CORONA - KVDC						DC DWV at 8.0 KV	
	After Post Cure*		After Thermal Shock*		After Life Test*		After Post Cure	After Thermal Shock
	CIV**	PC	CIV**	PC	CIV**	PC	Results	Results
8-1	N.T.	0	8.0	0	N.T.		Pass	Pass
8-2	8.0	2	8.0	37	L.F.		Pass	Pass
8-3	8.0	10	8.0	25	L.F.		Pass	Pass
8-4	8.0	100	8.0	70	L.F.		Pass	Pass
8-5	8.0							
8-6	N.T.	10	8.0	0	L.F.		Pass	Pass
8-7	8.0.	50	8.0	37	L.F.		Pass	Pass
8-8	8.0							
8-9	P.F.				L.F.			
8-10	N.T.							
8-11	8.0	0	8.0	0	8.0	2 (10)	Pass	Pass

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
P.F. - Previous failure
* - 8.0 KVDC max. test voltage
** - if pC = 0, then CIV assumed greater than 8.0KV
( ) - after 10 minutes

Table 38: DC High Voltage Characteristics for the Ricotuff LV - Polymat MTS HV Insulation Systems

MTS Serial Number	AC Breakdown Voltage (KVAC - RMS)	DC Equivalent Voltage (KVDC)	Electrical Stress-DC Equivalent (Volts/Mil)
8-9	4.5	6.3	2100
AV.	4.5	6.3	2100

Table 39: AC Electrical Breakdown Voltages and the Associated DC Equivalent and Values for the Ricotuff LV - Polymat HV Insulation Systems.

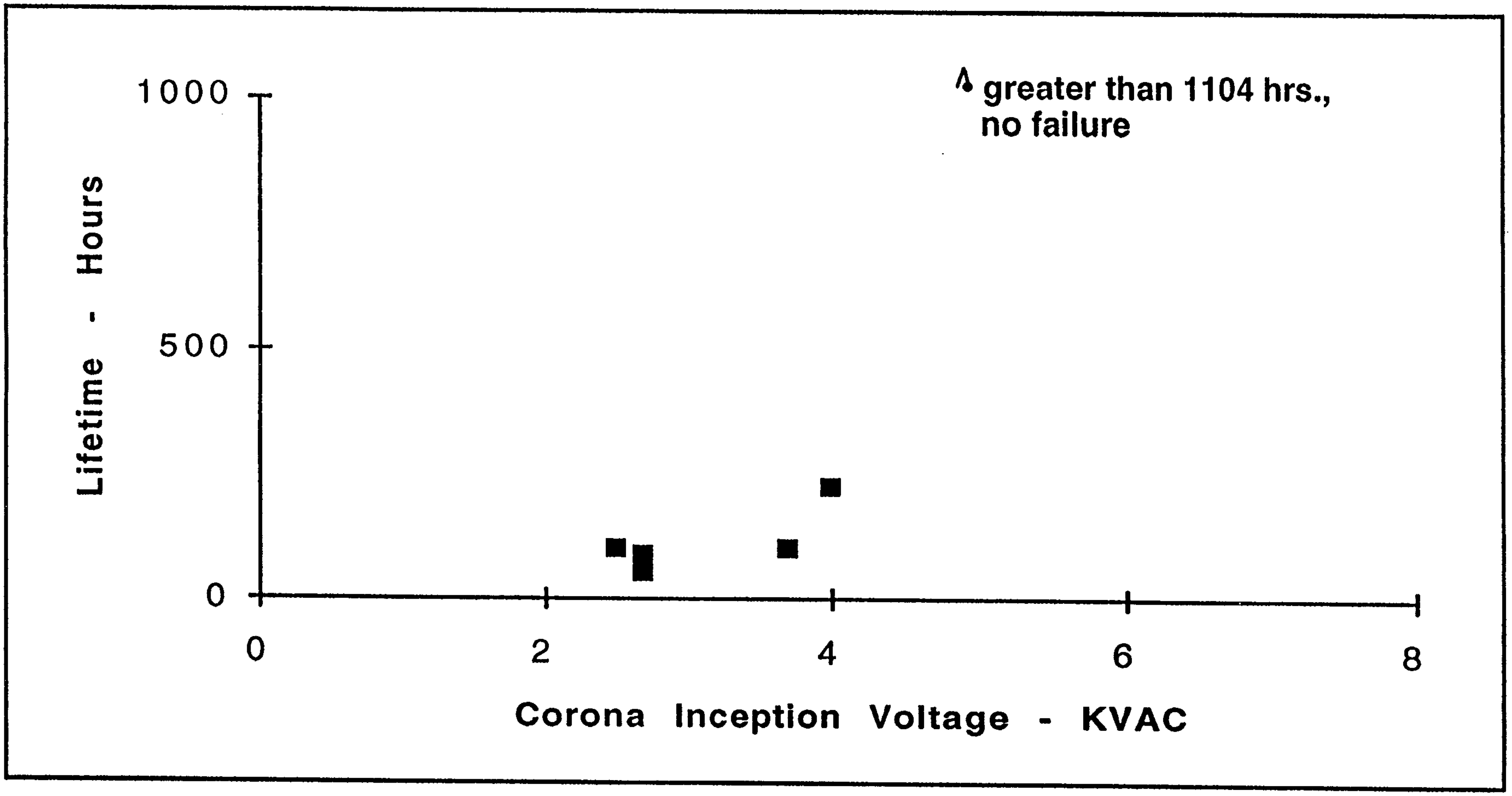


Figure 15

Relationships Between MTS Lifetimes and Corona AC Inception Voltages for Ricotuff LV - Polymat HV Insulation Systems

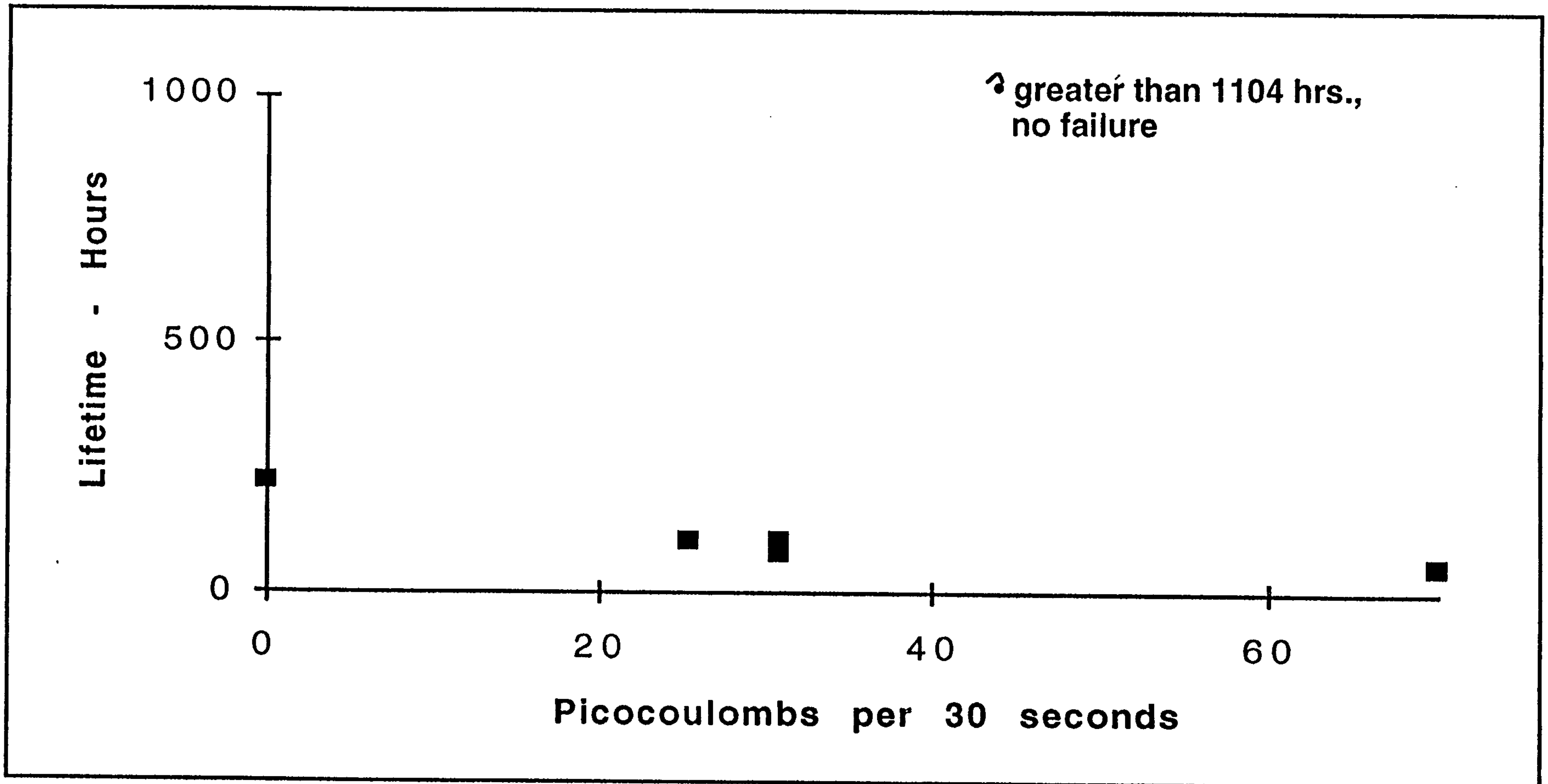


Figure 16

Relationship Between DC Corona Discharge Levels and MTS Lifetimes at 8.0KV for the Ricotuff LV - Polymat HV Insulation System

constant after thermal shock. These devices exhibited the lowest AC CIV levels of the four HV insulation systems evaluated. For these MTS's, only three devices produced CIVs approaching or equaling 6.0 KVAC.

Three MTS's had AC CIVs of 2.1 KVAC after the initial cure (Serial Numbers 8-3, 8-4, and 8-5), the lowest level observed. The highest levels noted were 6.0 KVAC for Serial Number 8-6, after the initial cure, and for Serial Number 8-11, after thermal shock. Serial Number 8-11 exhibited an AC CIV greater than 6.0 KVAC after life tests. The lowest CEV's were 1.4 KVAC observed for two devices (Serial Numbers 8-5 and 8-8). Serial Number 8-9 failed by electrical breakdown at 4.5 KVAC after post-cure.

The AC corona results for these MTS's are summarized in Table 37.

DC Corona. Five of the devices exhibited corona discharge at 8.0 KVDC. These discharge processes were detected following the post-cure. Of these five devices, one (Serial Number 8-7) produced no detectable discharge following thermal shock while the other four continued to exhibit DC corona. There were no DC corona measurements made after the initial cure.

The DC corona levels observed for these MTS's ranged from 0 for Serial Numbers 8-2 and 8-11 following both post-cure and thermal shock, and for Serial Number 8-7 after thermal shock. The latter device did exhibit a discharge level of 10 picocoulombs per 30 seconds following post-cure. Serial Number 8-5 produced the highest discharge levels at 100 and 70 picocoulombs per 30 seconds after post-cure and thermal shock. Serial Number 8-11 produced discharge levels of 2 and 10 picocoulombs after 30 seconds and 10 minutes following life tests.

The results of the DC corona tests for the Ricotuff LV - polymat MTS's are given in Table 38.

Modified Dielectric Withstanding Voltage. All of the MTS's tested passed the modified DWV tests which were performed after post-cure and thermal shock. None of the devices produced leakage currents exceeding the 50 nanoampere limit established as the Passing requirement for these evaluations.

The results of the DWV tests are presented in Table 38.

Thermal Shock. As has been noted all of the MTS's for this insulation system contained cracks following the initial cure. As with the other insulation systems, no attempt was made to map the cracks either before or after thermal shock. General observations before and after thermal shock, indicated very little change for these devices. These observations are supported by both the AC and DC corona test results in which minimal or no change in levels or values were detected for the before and after data.

Life - Time Tests. The life - times at 8.0 KVDC at room-temperature in air for the six MTS's tested ranged from 49 hours for Serial Number 8-5 to in excess of 1100 hours for Serial Number 8-11 which had not failed when testing for this Series was terminated at 1104 hours. The average time - to - failure for this Series was greater than 277 hours, ranking third of the four HV insulations evaluated. The life test results are presented in Figure 17.

The relationships between the corona characteristics and life - times are shown in Figures 15 and 16. Figure 15 presents the AC CIVs and the corresponding MTS life - times. Those devices exhibiting the lower CIVs produced the shortest life - times. The MTS which did not fail the highest CIV of the devices tested. A similar relationship is shown for the DC corona and MTS life - times in Figure 16. Those devices with the higher discharge levels yielded the shorter life - times. The MTS which did not fail produced no detectable DC corona before the life test. After the life test, this MTS exhibited 2 picocoulombs of discharge after 30 seconds and a total of 10 picocoulombs after 10 minutes.

Again, it should be noted that the MTS's used in these evaluations were flawed, and the resulting life - times are not representative of those which would be produced by devices which did not have these defects.

Electrical Breakdown Voltages. The electrical breakdown voltages for these MTS's were those produced during the AC corona tests. These AC results are RMS values and are presented in Table 39 along with the equivalent DC value.

Electrical Resistivities. The electrical resistivities for the Ricotuff LV - polymat insulation system are given in Table 43.

Scotchcast MR 283/U000 - Polymat. (see Tables 40 - 43; Figures 17 - 19.)

This Series of MTS's was the only one in which the test devices were essentially crack-free after the initial cure.

AC Corona. The AC corona levels for these MTS's exhibited the highest individual device CIV value and the highest group average CIV after the initial cure of the four HV insulations evaluated. Subsequent conditioning through post-cure and thermal shock resulted in reduced levels for both the CIV and CEV values for the majority of the MTS's tested.

The highest CIV value measured was 11.0 KVAC for Serial Number 9-7 which was coincident with the electrical breakdown of this test structure. The highest CIV value for a device which did not

AC CORONA - KVAC								
MTS SERIAL NUMBER	Before Post Cure		After Post Cure*		After Thermal Shock*		After Life Test*	
	CIV	CEV	CIV	CEV	CIV	CEV	CIV	CEV
9-1	10.9 (VBD)							
9-2	7.5	4.2					N.T.	
9-3	10.6 (VBD)							
9-4	9.9	5.6	>6.0	>6.0	>6.0	>6.0	L.T.	
9-5	7.7	5.2	5.9	5.6	5.6	3.1	N.T.	
9-6	7.8 (VBD)							
9-7	11.0 (VBD)							
9-8	5.7	3.4	3.3	2.4	2.4	1.8	L.F.	
9-9	N.T.		N.T.		3.5	1.9	L.F.	
9-10	6.0	4.3	4.2	3.6	4.4	3.0	N.T.	
Avg.	8.2	4.2	>5.1	>4.7	>4.6	>3.5	-	-
Std. Dev.	2.2	1.0	>1.1	>1.5	>1.4	>1.5		

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
* - 6.0 KVAC RMS max. test voltage
VBD - Voltage breakdown

Table 40: AC Corona Characteristics for the Scotchcast MR283/U000 - Polymat MTS HV Insulation Systems

DC CORONA - KVDC							DC DWV at 8.0 KV	
MTS SERIAL NUMBER	After Post Cure*		After Thermal Shock*		After Life Test		After Post Cure	After Thermal Shock
	CIV	CEV	CIV	CEV	CIV	CEV	Results	Results
9-1	P.F							
9-2	N.T.							
9-3	P.F.							
9-4	8.0	0	8.0	0	L.F.		Pass	Pass
9-5	8.0	0	8.0	0	N.T.		Pass	Pass
9-6	P.F.							
9-7	P.F.							
9-8	8.0	0	8.0	2	L.F.		Pass	Pass
9-9	8.0	0	8.0	12	L.F.		Pass	Pass
9-10	8.0	0	8.0	0	N.T.		Pass	Pass

MTS' immersed in Freon TF at room temperature
N.T. - Not tested
L.F. - Life test failure
P.F. - Previous failure
* - 8.0 KVDC max. test voltage
** - if pC = 0, then CIV assumed greater than 8.0KV

Table 41: DC High Voltage Characteristics for the Scotchcast - Polymat MTS HV Insulation Systems

MTS Serial Number	AC Breakdown Voltage (KVAC - RMS)	DC Equivalent Voltage (KVDC)	Electrical Stress-DC Equivalent (Volts/Mil)
9-1	10.9	15.4	5133.
9-3	10.6	14.9	4967.
9-6	7.8	11.0	3667.
9-7	11.0	15.5	5167.

Table 42: AC Electrical Breakdown Voltages and the Associated DC Equivalent and Values for the Scotchcast MR283/U000 - Polymat HV Insulation Systems.

		Room-Temp. Values		125°C Values	
HV Insulation System	MTS Serial Number	Leakage Current (pA)	Vol. Resist. (ohm-cm)	Leakage Current (pA)	Vol. Resist. (ohm-cm)
Epon 825/ HV	5-10	7.2	4.2.E16	1800.	1.7E14
AralditeCY, etc	7-1	5.4	5.6E16	360	8.4E14
Ricotuff LV	8-10	13.5	2.2E16	540	5.6E14
Scotchcast MR283/U000	9-2	7.4	4.1E16	2740.	1.1E14

V Test - 100.1 VDC
Electrification time - 2.0 minutes

Conditions:
Room temp - 22° - 26°C and 39 - 52% R.H.
Elevated temp - 124° - 127°C

Measurments after post-cures

Table 43: Electrical Resistivities for the Four Transformers HV Insulation Systems at Room - Temperature and 125°C

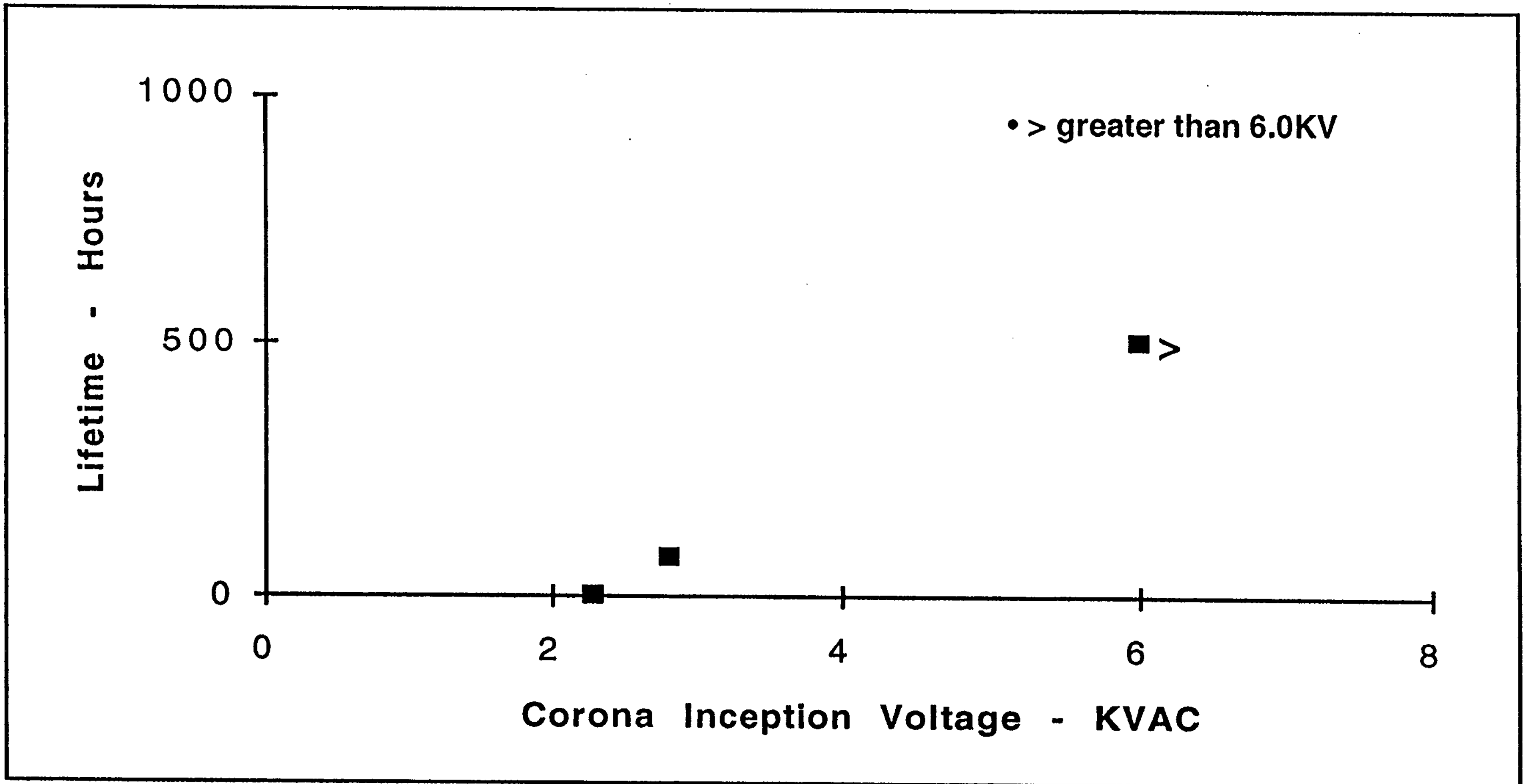


Figure 17

Relationships Between MTS Lifetimes and Corona AC Inception Voltages for Scotchcast MR283/U000 - Polymat HV Insulation System

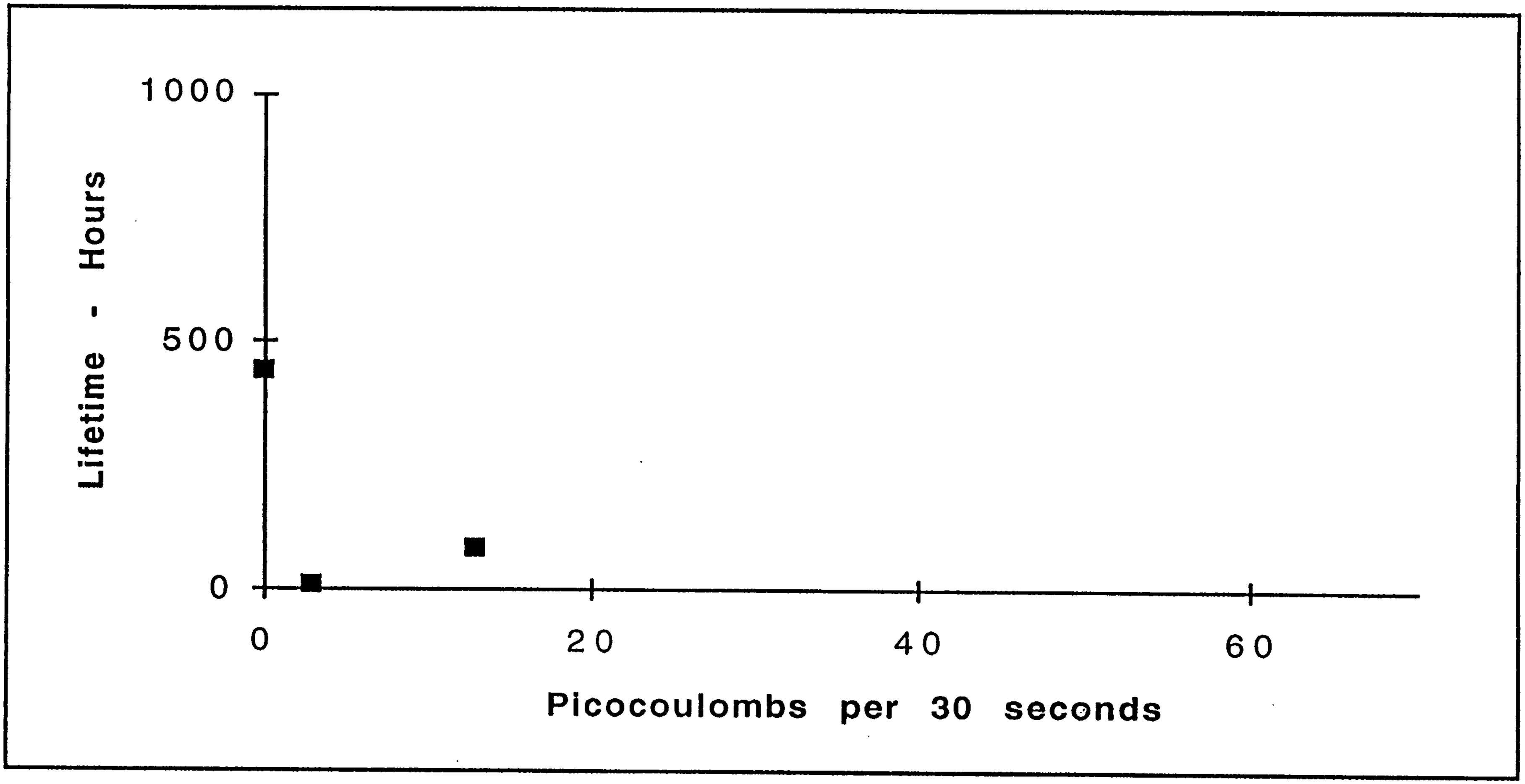
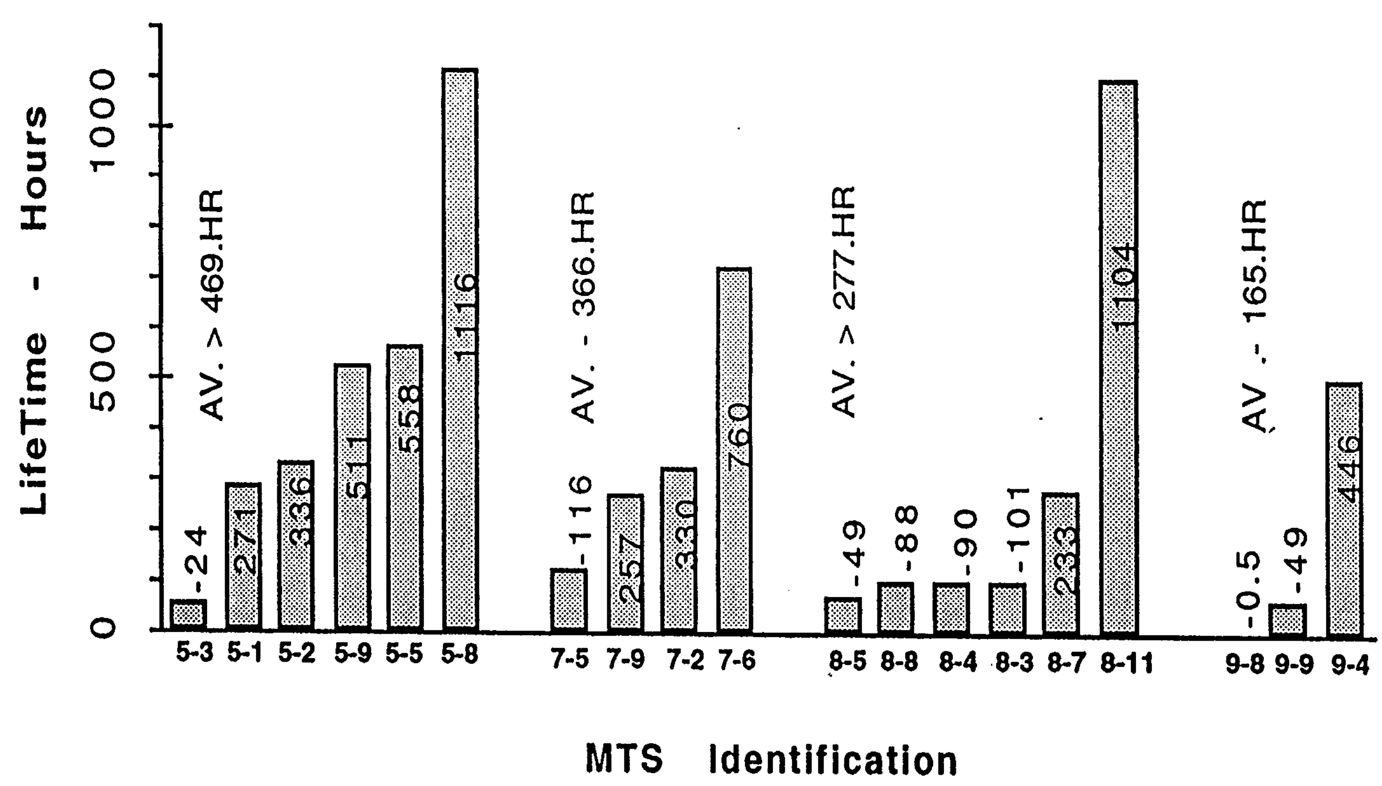


Figure 18

Relationships Between DC Corona Discharge Levels and MTS Lifetimes at 8.0KV For Scotchcast MR283/U000 - Polymat HV Insulation System



SERIES

5- X - Epon 825/HV

7- x - Aradlite Cy

8 - X - Ricotuff LV

9 - x - Scothcast MR283

CONDITIONS

- 8.25 KVDC
- Room Temp (20°-28°)
- R.H. (39-55%
- 2750 volts/mil AV. Stress

Figure 19

Life Time Test Results For The Hours Transfomer HV Insulation Systems

breakdown was 9.9 KVAC for Serial Number 9-4. The average CIV for the series was 8.2 KVAC after the initial cure. The lowest CIV observed for this series was 2.4 KVAC for Serial Number 9-8 following thermal shock. This same structure had a CIV of 5.7 kVAC after the initial cure which reduced to 3.3 KVAC following the post-cure. This same device exhibited the lowest CEV at 1.8 KVAC following thermal shock.

The AC corona results for these MTS's are given in Table 40.

<u>DC Corona</u>. The DC corona tests were performed only after post-cure and thermal shock. After the post-cure none of the test structures produced any detectable discharge during the measurement period. Following thermal shock, two of the five devices produced measured discharges.

Serial Number 9-8 produced 2 picocoulombs of discharge and Serial Number 9-9 12 picocoulombs during the 30 second test interval after thermal shock.

The DC corona results for these MTS's are presented in Table 41.

<u>Modified Dielectric Withstanding Voltage</u>. All of the devices tested passed the modified DWV test which was performed only after the post-cure and thermal shock. All of the devices produced leakage currents less than the 50 nanoampere limit established as the Pass criteria for this test.

The modified DWV test results are given in Table 41.

<u>Thermal Shock</u>. As previously noted the MTS's of this series were the only ones which were not cracked after the initial cure. While all of the MTS's tested exhibited some reduction in the AC corona levels following post-cure no noticeable cracking was observed. Following thermal shock, again, no noticeable cracks were detected. As noted above, there were changes in the corona characteristics following thermal shock which could not be related to observable physical defects.

<u>Life - Time Tests</u>. The life - times at 8.0 KVDC at room-temperature in air ranged from 0.5 hours for Serial Number 9-8 to 446 hours for Serial Number 9-4. The average life - time for the three devices tested in this series was 165 hours. This ranked this insulation fourth of the four systems evaluated. The results of the life - time tests are summarized in Figure 19.

The relationships between the corona characteristics and the DC HV life - times are presented in Figures 17 and 18. Figure 17 shows the relation between the AC CIVs and the life - times of the three MTS's tested. These results show a definite relation between the CIV levels and device life - time. The shortest life - time resulted from the device with the lowest AC CIV (Serial Number 9-8) with the longest life - time produced by the device with the highest AC CIV (Serial Number 9-4). Figure 18 shows the relation between the DC corona discharge level and the MTS life - times. Here a reasonable relation is observed the discharge level and life - time with the two devices (Serial Numbers 9-8 and 9-9) which produced detectable discharge during the DC corona tests having the shortest life - times. Serial Number 9-4 which had the longest life - time of this series produced no detectable discharge during the DC corona tests and yielded a life - time which was more than 20 times the average of the other two devices.

Since the MTS's did not show obvious physical defects, yet did exhibit low corona levels following post-cure and thermal shock, it may be assumed that the life - times produced by this insulation system are representative of those which could be expected for similar constructions.

Electrical Breakdown Voltages. The electrical breakdown voltages for these MTS's are those which were produced during the AC corona tests. The values measured were RMS values and are presented in Table 42 along with their DC equivalents. No direct DC breakdown determinations were made.

Electrical Resistivities. The electrical resistivities for the Scotchcast MR 283/U000 - polymat system are given in Table 43.

C2 Summary.

This section has described and demonstrated a set of procedures for determining the HV characteristics of HV transformer insulation systems. From these demonstrations, the following observations and conclusions can be drawn.

All of the MTS's employed in these determinations demonstrated the existence of AC corona at some level at some time during their evaluations. The CIV levels ranged from approximately 2 to 11 KVAC RMS. This occurrence of AC corona indicates the presence of form of physical defect to exist in each of the test structures. The variation in the CIV values is associated with the location and size of the physical defect. The exception to the occurrence of physical defects associated with the CIV value might be those MTS's which failed via voltage breakdown during these AC tests at voltages of 10 KVAC RMS and above. At these electrical stress levels which are approaching or exceeding 5000 volts per mil electrical breakdown can occur in the absence of physical defects.

When the various MTS's were subsequently HVDC life tested, a reasonable correlation was observed between the AC CIV levels and the life-time of the device. Lower levels of CIV resulted in lower life-times. This relation existed for each of the four HV insulation systems. These results support the general use of AC corona testing as a product quality indicator.

The principle determination from the DC corona tests was that the corona monitoring period at the test voltage was insufficient. This determination is based on the general absence of detectable corona during the 30 second measurement period at the 8.0 KVDC test voltage. When MTS's were subsequently life tested at the same voltage 17 of 19 devices failed in less than 800 hours with an average time-to-failure of approximately 200 hours. The only process by which such failures could occur is some form of DC corona discharge which was generally not detected in the DC corona tests. The two MTS's which did not fail during the 1100 hour life test time were DC corona tested subsequently with the monitor period extended to 10 minutes. One device (Serial Number 5-8) produced no detected discharge and the other (Serial Number 8-11) yielded 10 picocoulombs of discharge during the test period. Both conditions would be expected to yield long life products which were the results indicated in these tests.

For the four MTS's which did exhibit DC corona discharge in the post thermal shock tests (Series 8 devices), the discharge levels showed reasonable correlation with the DC life-times. Here the higher discharge levels were associated with the shorter life-times which is the relationship to be expected.

Life test results have shown the relationships between the AC corona CIVs and to a somewhat lesser extent the DC corona discharge levels and the DC HV life-times for the MTS's of the various insulation systems. As has been noted for each of the HV insulation results, most of the MTS's tested had cracks. The reason for the cracks and the use of cracked devices has been stated. The use of the cracked devices has allowed the demonstration of the corona - life-time relationships occurring in these tests. In the absence of these flaws, the life-times of the devices would have most probably been much longer and might not have been demonstrable during this program. These conclusions are suggested based on the results of the two devices which did not fail during 1100 hours of life testing. Both devices when examined after life tests were found to be free of cracks in the high electric field areas which accounts in part for the fact that they did not fail. The absence of cracks in these devices and their demonstrated life-times in these tests indicate the long lives which might be expected from these insulation systems when produced flaw free. Similarly, the life-times for the flawed MTS's are not those which would probably exist had flaw free devices of the same materials been evaluated.

The results of the thermal shock tests are somewhat ambiguous. Some MTS's showed increased AC CIV values following thermal shock while others experienced reductions and others were unchanged. The general absence of DC corona before and after thermal shock is likely the result of the duration of the monitor period. The Scotchcast MR 283 - polymat system which had not cracks following the initial and post cures showed no cracks after thermal shock. The AC CIV values for this system were reduced following thermal shock which would indicate some physical change did occur during this exposure even though it was not visual noticed. The other three insulation systems showed the variable results described above. The absence of uniform responses for these three systems is likely due to the flaws which were originally present in most of these MTS's. The absence of uniform responses in these tests should not diminish the importance of thermal shock testing in evaluating HV insulation systems. This test in combination with corona and life testing is probably the most important in establishing the viability of HV insulation systems.

Although not recorded, variations were observed in the associated DC leakage currents present during the modified DWV testing of the MTS's. The variations could be group both by insulation system and individual MTS. The group variations can be related to the resistivities of the various systems. The individual variations within a group may be related to the quality and the integrity of the MTS. Since the individual values were not recorded no correlation can be made between these leakage currents and the associated life-times and corona characteristics. It is possible that such relations due exist and that such relations might be used in the quality monitoring process.

No DC electrical breakdown tests were performed in these evaluations. This resulted because of insufficient MTS's in each insulation series. This insufficiency was due in part to failures occurring in the AC corona tests following the initial cure. The AC breakdown values for those devices which failed during these AC tests have been related to their DC equivalents which provides a general indication of the short time voltage withstanding capability for the insulation systems. Although not performed here, DC electrical breakdown tests on representative samples are recommended when evaluating and selecting HV insulation systems.

CONCLUSIONS

This activity has demonstrated the multiple uses which Model Test Structures can serve. In these evaluations, MTS's were used to assess the processabilities of candidate HV insulation systems. The same MTS's were then used to determine the AC loss properties and the HV characteristics of the same insulation systems resulting from the processability studies.

The insulation systems exhibiting preferred processabilities for transformer HV insulation applications were the Araldite CY 9729,.-polymat and the Scotchcast MR 283/U000-polymat systems. Both resin systems have long working life-times and low viscosities. These attributes in combination with low surface tensions are those generally required to effectively produce a HV transformer insulation product. The cure schedules for both materials would also be compatible with the other materials used in transformer construction.

The insulations system exhibiting the lowest AC loss was the Ricotuff LV. At the higher temperatures and frequencies the Epon 825/HV-polymat system has AC loss characteristics comparable to the Ricotuff LV product.

Selection of preferred HV insulation systems from the HV characterization evaluations is complicated by the results produced by the cracked MTS's. Based on the results of the evaluations, the Epon 825/HV-polymat system demonstrated the overall highest level of performance.

When processability, AC loss and HV performance are considered in combination, the Epon 825/HV-polymat system is the preferred system as a transformer HV insulation of the four materials evaluated in these studies.

2.4 Corona And Breakdown Performance Of Specific Materials Using Printed Wiring Board Model Test Structures

Potentially significant advantages could accrue from the use of printed wiring boards (PWBs) for HV interconnects in HVPSs. The use of PWBs could simplify the assembly process by eliminating the need for hand wiring of those conductors, by eliminating some of the interconnections in the HVPS, by eliminating the need for careful positioning of conductors, by eliminating the possibility that conductors can move during the potting process, and by establishing fixed and repeatable locations for the electronic components attached to the PWB.

However, theuse of PWB for HV interconnections in HVPSs has been limited by performance concerns. Specifically, concerns have been expressed about the ability of PWB materials to withstand dielectric breakdown and corona discharge, and the effect that specific conductor spacings and geometries have on these propeties of the power supply. To shed light on these issues, and as an early demonstration of the MTS-DOE concept, Hughes performed a designed experiment on polyimide PWBs to test their suitability as HV interconnections for HVPSs.

One of the parameters to be tested in this experiment stemmed from certain workers' strongly held view that the corners of the PWB traces would be the most common *locii* for corona discharge and electrical breakdown taking place between traces that were held at a high voltage, and neighboring traces that were at ground potential or at some low voltage. As a consequence, they asserted, all HV PWBs should be designed only with curved traces. Other workers contended that these features were not more unique than the "sharp, 90° edges" on the tops of all PWB traces. The MTS-DOE method is ideally suited to resolve such technical disputes. For the study, we therefore designed two PWB MTSs, one of which incorporated square-cornered traces and the other of which incorporated curved traces.

In the language of DOE, this represented a single factor (independent variable), that was present at two levels (square-cornered and curved) in the MTSs. The MTSs also incorporated three other factors, 1) the spacing between conductors held at different potentials, 2) the presence or absence of a ground plane on the back of the MTS and, 3) the type of encapsulant used to pot the PWB traces. The inter-conductor spacing factor was present at three levels in each MTS - 30 mils, 60 mils, and 120 mils. The ground plane factor was had two levels on each MTS - its presence (connected to ground), or its absence (not connected and allowed to float).

To test the ability of the PWB to carry high voltages without damage, each MTS had sets of adjacent conductors that could be held at different potentials. The designs incorporated sets of three nested shapes - either squares or curves. An example of the square design is shown in Figure 1 of volume 3, section 1.2 of this report. In each case the inner and outer conductors of each nested set were electrically connected to each other, and to all of the other inner and outer conductors on the MTS. There was one electrical connection brought out from these conductors to the external test circuitry, and they were intended as a common ground. The middle conductors of each nested set were electrically independent, and each was brought out separately from the MTS. Each MTS incorporated three repetitions for each interconductor spacing, so that there were nine patterns on each board. As shown in Figure 1 of volume 3, section 1.2 of this report, the square-cornered MTS was designed so that the spacing between the tip of the corner and the neares adjacent metallization surface was the same as the inter-conductor spacing.

Figure 2 of volume 3, section 1.2 of this report, shows photographs of both sides of the square-cornered MTS. The photograph on the right shows the back side of the board, with its ground plane. Figure 3 of volume 3, section 1.2 of this report, shows photographs of both sides of the MTS with curved traces. Figure 4 of volume 3, section 1.2 of this report, shows a photograph of an encapsulated MTS. For encapsulation, a mold was made that covered the full extent of all of the nested patterns, but did not cover all of the ten traces at the edges of the MTSs that were the electrical connections. In this way, the wires that had been soldered to the ends of each trace before encapsulation (shown in Figure 4) could be un-soldered and reworked, if necessary.

An initial set of tests were performed to see the effects of test conditions and test media on the initial breakdown voltage for the MTSs. In the case of the tests labelled "air", the unencapsulated PWB MTSs were tested in air under room ambient conditions. In the case of the tests labelled "Freon TF", unencapsulated PWB MTSs were immersed in Freon TF at room temperature for testing. In the case of the tests labelled "Epon 825/HV" the MTSs were encapsulated in the pottant as shown in Figure 4 of volume 3, section 1.2 of this report, and were immersed in Freon TF at room temperature for testing.

Test Media

Conductor Spacing (mils)	Air (1) Square	Air (1) Curved	Freon TF (2) Square	Freon TF (2) Curved	Epon 825/HV (3) Square	Epon 825/HV (3) Curved
30	0.8 - 1.0	0.7 - 1.2	8.7 - 9.1	8.8 - 9.7	52 - 59	17
60	2.9 - 3.2	2.8 - 3.3	14.0-15.3	17.4-17.8	75 (fail 45 sec)	75 (no fail 5 min)
120	4.7 - 4.9	5.1 - 5.2	20.1-20.6	24.2-24.8	-	-

Table 1. Initial DC breakdown voltage levels (VDC) for PWB MTSs tested in various media.

Clearly, unencapsulated PWBs using these materials and interconductor spacings would not be suitable for the HV conductors in an HVPS. However, the MTSs placed in Freon TF did show behavior which may be suitable in many HVPS applications, and those encapsulated in Epon 825/HV would be suitable for most applications.

Other similar PWB MTSs were encasulated in other materials, and were then immersed in Freon TF, at room temperature, for AC and DC corona testing, and AC and DC breakdown voltage testing. The results of these analyses are shown in the remaining tables.

In general, this data shows that the MTSs with curved traces have slightly higher CIVs and VBDs than do their square-cornered counterparts. These are desireable properties for PWBs intended for HVPS applications. However, the differences observed are not large enough to suggest that square-cornered PWB design would not be suitable for HVPS interconnections. The AC and DC corona and breakdown voltage characteristics reported here suggest that PWBs would be suitable for HV interconnections for many HVPS applications.

TABLE 2. CRITICAL ELECTRIC FIELD CHARACTERISTICS FOR HV PWB MTSs ENCAPSULATED WITH EPON 825/HV

CONDUCTOR CONFIG.	CONDUCTOR SPACING (MILS)	PATTERN NO.	ac CIV kVac	ac VBD (kVac)	dc CIV kVac	dc VBD (kVac)
Square	30	1	-	22.2	-	-
		2	-	-	-	52
		3	-	-	-	59
	60	1	29.2	29.2	-	-
		2	-	-	75	75 (aft 45 sec)
		3	not tested			
	120	1	29.7	29.9	-	-
		2	-	-	-	-
		3	not tested			
Curved	30	1	17.8	18.1	-	
		2	-	-	-	1.9
		3	not tested			
	60	1	-	-	-	-
					75. (5 min - no fail)	
		2	-	33.8	-	-
		3	not tested			
	120	1	-	41.1	-	-
		2	not tested			
		3			-	-

TABLE 3. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR SQUARE CORNER AND PWB MTSs ENCAPSULATED WITH SCOTCHCAST 280

Spacing - Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30 - 1	12.8	4.1	13.2
2	12.1	4.4	12.4
3	---	---	---
60 - 1	16.0	6.4	19.3
2	15.8	4.4	21.8
3	---	---	---
120 - 1	17.7	7.1	28.4
2	16.6	6.6	26.8
3	---	---	---

TABLE 4. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR CURVED-CONDUCTOR HV PWB MTSs ENCAPSULATED WITH SCOTCHCAST 280 (TRACE-TO-TRACE VALUES)

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	13.7	7.1	15.7
	2	14.4	8.7	16.3
	3	Not Tested		
60	1	20.1	9.7	23.8
	2	21.4	11.2	24.0
	3	Not tested		
120	1	22.4	9.4	30.3
	2	22.7	11.0	30.3
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 5. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR SQUARE CORNER AND PWB MTSs ENCAPSULATED WITH SCOTCHCAST 281

Spacing - Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30 - 1	13.1	5.5	14.1
2	13.1	5.6	14.3
3	---	---	---
60 - 1	15.1	5.8	20.3
2	16.8	4.2	20.8
3	---	---	---
120 - 1	17.3	6.9	29.1
2	18.5	7.2	26.7
3	---	---	---

TABLE 6. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR CURVED-CONDUCTOR HV PWB MTSs ENCAPSULATED WITH SCOTCHCAST 281 (TRACE-TO-TRACE VALUES)

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	15.0	9.1	15.6
	2	15.5	8.4	15.6
	3	Not Tested		
60	1	-	-	22.8
	2	21,0	13.3	23.8
	3	Not tested		
120	1	20.4	10.4	28.7
	2	24.1	12.4	28.0
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 7. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR SQUARE CORNERED HV PWB MTSs ENCAPSULATED WITH URALANE 5753

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	-	-	8.0
	2	-	-	8.23
	3	Not Tested		
60	1	11.7	3.2	10.3*
	2	10.6	3.2	10.5*
	3	Not tested		
120	1	10.3	3.8	18.4
	2	11.7	4.5	18.9
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 8. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR CURVED CONDUCTOR HV PWB MTSs ENCAPSULATED WITH URALANE 5753

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	-	-	9.5
	2	-	-	11.6
	3	Not Tested		
60	1	13.7	5.1	12.1*
	2	15.5	5.2	11.9*
	3	Not tested		
120	1	16.7	5.0	19.8
	2	17.5	5.2	21.2
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

* - determined after CEV

TABLE 9. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR SQUARE CORNERED HV PWB MTSs ENCAPSULATED WITH STYCAST 2850FT

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	Values not recorded		
	2	6.1	4.1	18.4
	3	Not Tested		
60	1	18.0	14.5	23.3
	2	7.1	5.5	22.8
	3	Not tested		
120	1	12.6	8.4	27.2
	2	24.5	12.5	31.8
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 10 . AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISITICS FOR CURVED CONDUCTOR HV PWB MTSs ENCAPSULATED WITH STYCAST 2850FT

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	10.2	4.5	24.2
	2	14.8	6.5	20.5
	3	Not Tested		
60	1	12.2	6.5	29.9
	2	appears to have failed during test of (1)		
	3	Not tested		
120	1	21.5	11.2	34.2
	2	appear to have failed during test of (1)		
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 11. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR SQUARE CORNERED HV PWB MTSs ENCAPSULATED WITH EPON 825/HV-ALUMINA (1:1)

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	-	-	17.5
	2	-	-	20.5
	3	Not Tested		
60	1	26.5	4.5	28.4
	2			18.8
	3	Not tested		
120	1	28.1	19.1	29.0
	2	28.8	20.9	28.9
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 12. AC CORONA AND ELECTRICAL BREAKDOWN CHARACTERISTICS FOR CURVED CONDUCTOR HV PWB MTSs ENCAPSULATED WITH EPON 825/HV-ALUMINA (1:1)

Electrode Spacing (mils)	Pattern No.	CIV (kVac)	CEV (kVac)	VBD (kVac)
30	1	-	-	21.2
	2	-	-	23.2
	3	Not Tested		
60	1	22.5	17.8	29.5
	2	23.6	17.1	29.7
	3	Not tested		
120	1	26.1	21.1	34.8
	2	26.7	20.7	31.6
	3	Not tested		

Note: All measurements made with sample immersed in Freon TF at room temp.

TABLE 13. DC HIGH VOLTAGE CHARACTERISTICS OF SQUARE-CORNERED PWB MTSs AS A FUNCTION OF ENCAPSULANT TYPE (SHEET 2 OF 2)

Encapsulant	Conductor Spacing (mils)	Test Set	CIV (kVdc)*	CEV (kVdc)	V_{BD} (kVdc)
Stycast 2850 FT	30	30-1	NDC	-	60
		-2	40	32	55
		-3	28	20	46
	60	60-1	41	36	75**
		-2	55	50	75**
		-3	48	41	75**
	120	120-1	54	47	46
		-2	56	47	47
		-3	54	47	71
Epon 825/HV	30	30-1	51	40	67
		-2	51	44	67
		-3	52	43	64
	60	60-1	53	49	75**
		-2	53	47	75**
		-3	53	44	75**
	120	120-1	34	18	75**
		-2	39	26	75**
		-3	39	29	75**
Epon 825/HV with Al_2O_3 filler, 325 mesh (1:1 weight ratio)	30	30-1	39	32	59
		-2	33	25	60
		-3	33	24	63
	60	60-1	39	33	58
		-2	39	33	58
		-3	37	32	75
	120	120-1	34	29	61
		-2	36	31	59
		-3	37	33	75**

Conditions: MTSs immersed in Freon TF at room temperature
*NDC = no detectable corona
**No V_{BD} after 1.0 minute

TABLE 14. DC HIGH VOLTAGE CHARACTERISTICS OF SQUARE-CORNERED PWB MTSs AS A FUNCTION OF ENCAPSULANT TYPE (SHEET 1 OF 2)

Encapsulant	Conductor Spacing (mils)	Test Set	CIV (kVdc)*	CEV (kVdc)	V_{BD} (kVdc)
Scotchcast 280	30	30-1	39	36	75**
		-2	40	29	75**
		-3	41	37	75
	60	60-1	42	36	70
		-2	12	10	10
		-3	41	33	65
	120	120-1	58	25	75 @ 20 sec.
		-2	NDC	-	1.0
		-3	30	22	75 @ 30 sec.
Scotchcast 281	30	30-1	44	36	59
		-2	43	35	47
		-3	49	36	53
	60	60-1	NDC	-	49
		-2	39	31	64
		-3	46	38	72
	120	120-1	39	26	75**
		-2	48	40	75**
		-3	50	43	75**
Uralane 5753	30	30-1	NDC	-	35
		-2	NDC	-	34
		-3	NDC	-	35
	60	60-1	NDC	-	36
		-2	40	35	60
		-3	42	37	75
	120	120-1	40	35	75
		-2	42	37	66
		-3	47	40	55

Conditions: MTSs immersed in Freon TF at room temperature
*NDC = no detectable corona
**No V_{BD} after 1.0 minute

TABLE 15. DC HIGH VOLTAGE CHARACTERISTICS OF CURVED-CONDUCTOR PWB MTSs AS A FUNCTION OF ENCAPSULANT TYPE (SHEET 2 OF 2)

Encapsulant	Conductor Spacing (mils)	Test Set	CIV (kVdc)*	CEV (kVdc)	V_{BD} (kVdc)
Stycast 2850 FT	30	30-1	26	18	40
		-2	24	17	54
		-3	28	19	29
	60	60-1	50	43	75 @ 60 sec.
		-2	49	42	65
		-3	47	41	72
	120	120-1	54	42	75**
		-2	59	49	75**
		-3	65	56	75**
Epon 825/HV	30	30-1	49	44	75 @ 40 sec.
		-2	45	39	39
		-3	38	33	75
	60	60-1	43	35	75**
		-2	54	49	75**
		-3	55	48	75**
	120	120-1	52	47	75**
		-2	54	49	75**
		-3	53	48	75**
Epon 825/HV with Al_2O_3 filler, 325 mesh (1:1 weight ratio)	30	30-1	NDC	-	45
		-2	42	30	56
		-3	49	42	58
	60	60-1	62	54	54
		-2	NDC	-	56
		-3	NDC	-	44
	120	120-1	45	38	75**
		-2	53	46	75**
		-3	NDC	-	54

Conditions: MTSs immersed in Freon TF at room temperature

*NDC = no detectable corona

**No V_{BD} after 1.0 minute

TABLE 16. DC HIGH VOLTAGE CHARACTERISTICS OF CURVED-CONDUCTOR PWB MTSs AS A FUNCTION OF ENCAPSULANT TYPE (SHEET 1 OF 2)

Encapsulant	Conductor Spacing (mils)	Test Set	CIV (kVdc)*	CEV (kVdc)	V_{BD} (kVdc)
Scotchcast 280	30	30-1	45	39	66
		-2	NDC	-	2
		-3	50	44	70
	60	60-1	53	43	75 @ 12 sec.
		-2	64	56	72
		-3	56	43	75 @ 6 sec.
	120	120-1	65	54	75**
		-2	64	55	75**
		-3	65	56	75**
Scotchcast 281	30	30-1	35	26	54
		-2	NDC	-	50
		-3	NDC	-	~1
	60	60-1	56	47	75**
		-2	41	32	75**
		-3	45	27	75**
	120	120-1	40	32	75**
		-2	47	35	75**
		-3	42	30	75**
Uralane 5753	30	30-1	NDC	-	24
		-2	37	28	39
		-3	31	24	33
	60	60-1	55	48	73
		-2	52	46	68
		-3	51	41	52
	120	120-1	53	45	69
		-2	55	47	60
		-3	54	46	59

Conditions: MTSs immersed in Freon TF at room temperature

*NDC = no detectable corona

**No V_{BD} after 1.0 minute

2.5 Evaluation OF High Voltage Diodes Using Model Test Structures

ABSTRACT

Temperature measurements were made on encapsulated high voltage rectifier diode arrays using thermocouples attached to the diode leads and cases. With the diodes dissipating 500 mw each in the forward mode, evidence was developed indicating approximately equal loss of heat via the leads and the case.

Suggestions are made for better instrumented experiments, using thermocouples or infrared thermography, which would give more precise values for the ratio of heat transfer via body and leads.

DESCRIPTION OF EXPERIMENT

A Model Test Structure (MTS) per Section 1.5 - consisting of three series connected high voltage rectifier diodes encapsulated in an unfilled epoxy resin (Epon 825/HV) - was used as the vehicle for determining heat transfer paths.

Two MTSs were constructed for these evaluations. One employed glass encased diodes, and the other used molded plastic packaged devices.

Each experimental run consisted of passing 500 ma of forward current through all three diodes, or only the center one, while the body temperature and one lead temperature were monitored on a 3-channel chart recorder. The third channel was used to monitor the surface temperature or the forward voltage drop.

Figure 4 shows the beginning and end of a typical experimental run. In this example the diode cases were glass, and current passed through all three diodes in series. When the power was turned on (lower right corner of the chart), the thermocouple voltage (proportional to temperature) rose immediately and simultaneously in the lead and body locations. At the outer surface of the epoxy block (encapsulation), however, there was a delay of about 20 seconds. This was expected because of the greater distance and the low thermal diffusivity of the epoxy as compared to copper or Dumet.

Similarly, at the end of the run where power was switched off (left of chart), the temperature plunged suddenly both in the leads and the body, but only after a delay at the block surface. These observations indicated a much lower thermal resistance between leads and body than between either one and the encapsulation surface.

Beginning and end of a typical 35 minute run during which temperature was recorded on the leads, body, and encapsulation surface. Note that the lead and body temperatures rose and fell simultaneously, but that there was a time lag of about 20 seconds at the epoxy surface.

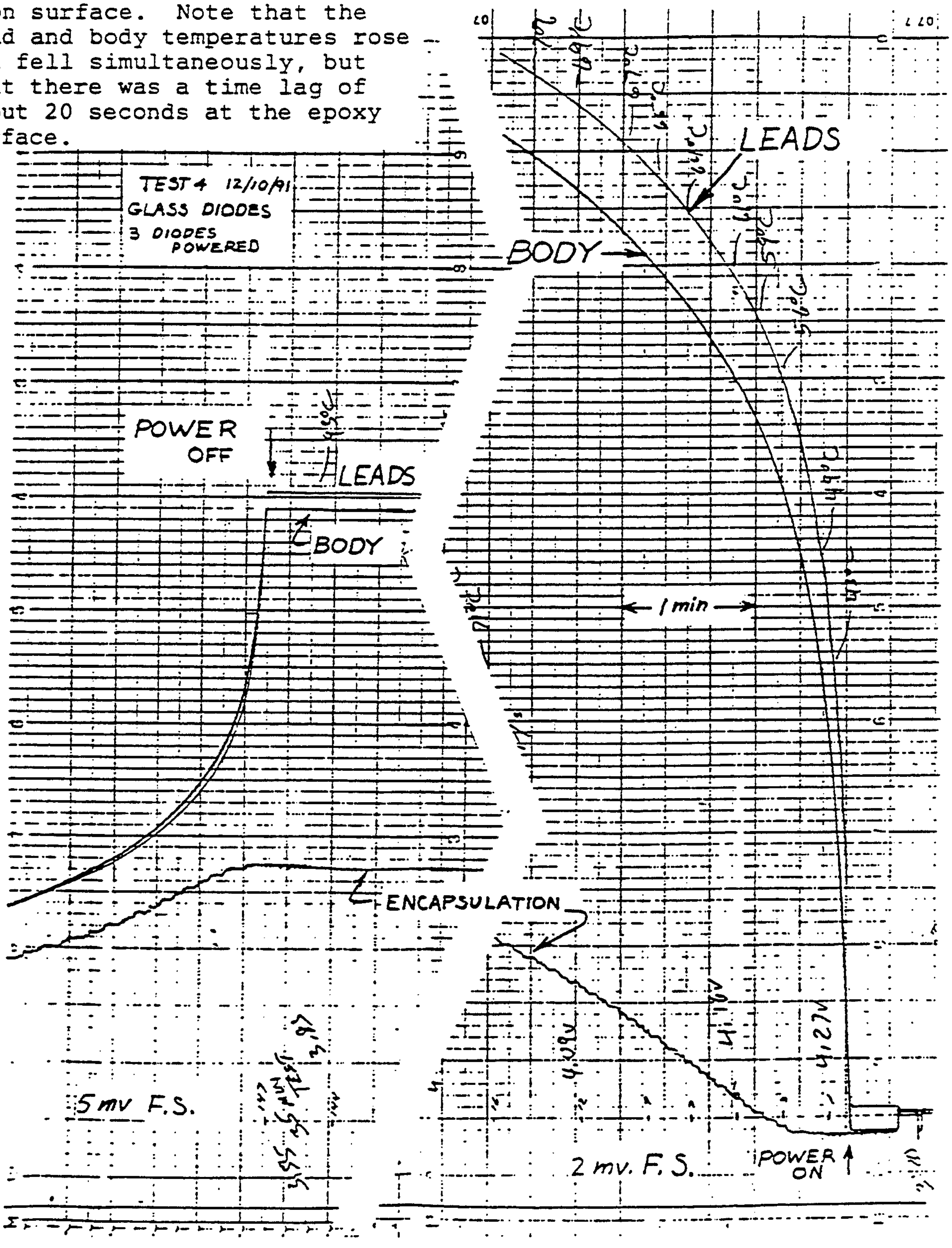


Figure 4. Test No. 4 Results, 3 Glass Diodes

A second generalization appeared when runs in which all three diodes were powered were compared with runs in which only the center diode was powered. When all diodes were generating heat, the lead was hotter than the body, but when only the central one was powered, the body was hotter. Figure 5 shows two such runs replotted on a convenient scale for comparison.

This behavior can be understood qualitatively by referring to the thermal network of Figure 6, which was drawn for the central diode. The thermal resistances R, are very small, R_2 somewhat larger, and R_3, R'_3 much larger. Temperatures could be measured only at the LEAD and BODY nodes and at the surface. The DIE node was inaccessible.

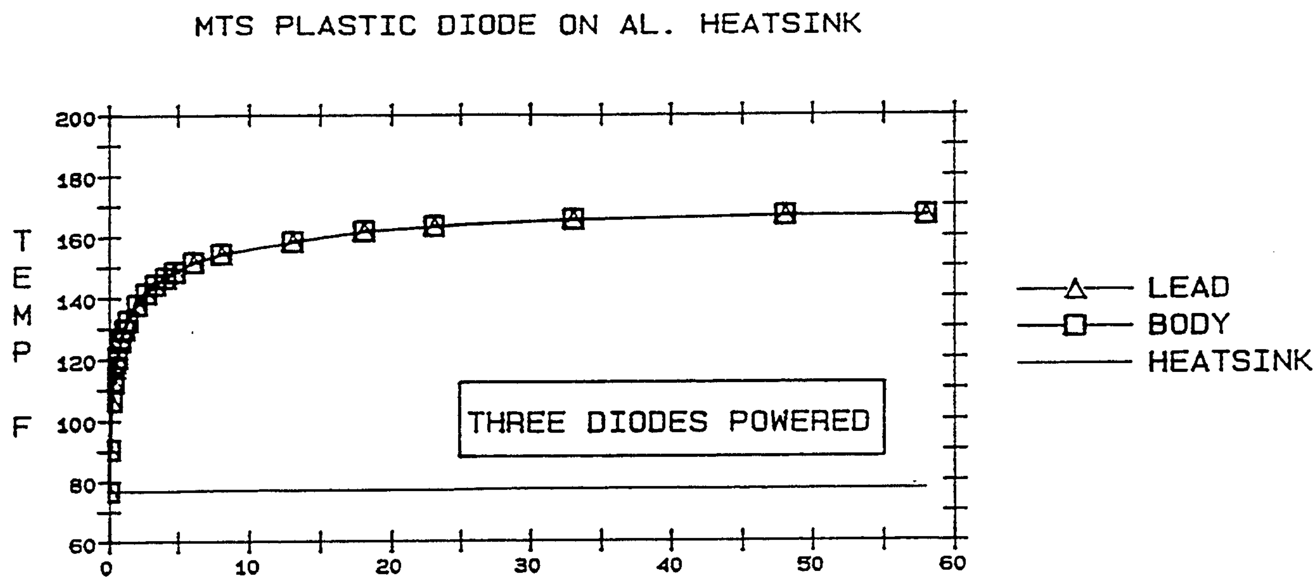
When only the center diode was heated, heat was conducted away from the LEAD nodes to the right and left. When the two outer diodes were also heated, they acted somewhat like guard heaters, and the effect was to greatly reduce or prevent the conduction of heat by this path. As a result, the leads ran at a higher temperature and were warmer than the body.

To estimate the relative heat flux out of the diode via the leads and via the body, it is necessary to measure temperature at enough points to allow estimates of temperature gradients. Since we know or can measure thermal conductivities, we can (in principle) calculate the steady-state heat flows from geometry and the temperatures measured at a sufficient number of well-chosen points.

The three thermocouple locations chosen here for measurement were not nearly enough for precise evaluation of the heat flows through the network of Figure 6. However, we can still estimate the ratio of heat flows through the leads (R_1, R_3) and the body (R_1, R_2, R'_3). To do this, we compare the body temperature when only the center diode is powered with the higher temperature obtained when all three diodes are powered. Both test runs must be done at the same current level with sufficient time allowed for a steady state to be reached.

We make the assumptions (neither of them exact) that the temperature differences are proportional to heat flow, and that the effect of powering the end diodes is merely to prevent heat flow out the leads of the center diode.

Stated another way, we assume that when only the center diode is powered, a fraction F of the total power dissipation, Q_{total}, is conducted out the diode case, but when all 3 diodes are powered, then the center diode must conduct all of this heat out the case. Since the current is the same in both cases, the same total power output (for each diode) is involved.



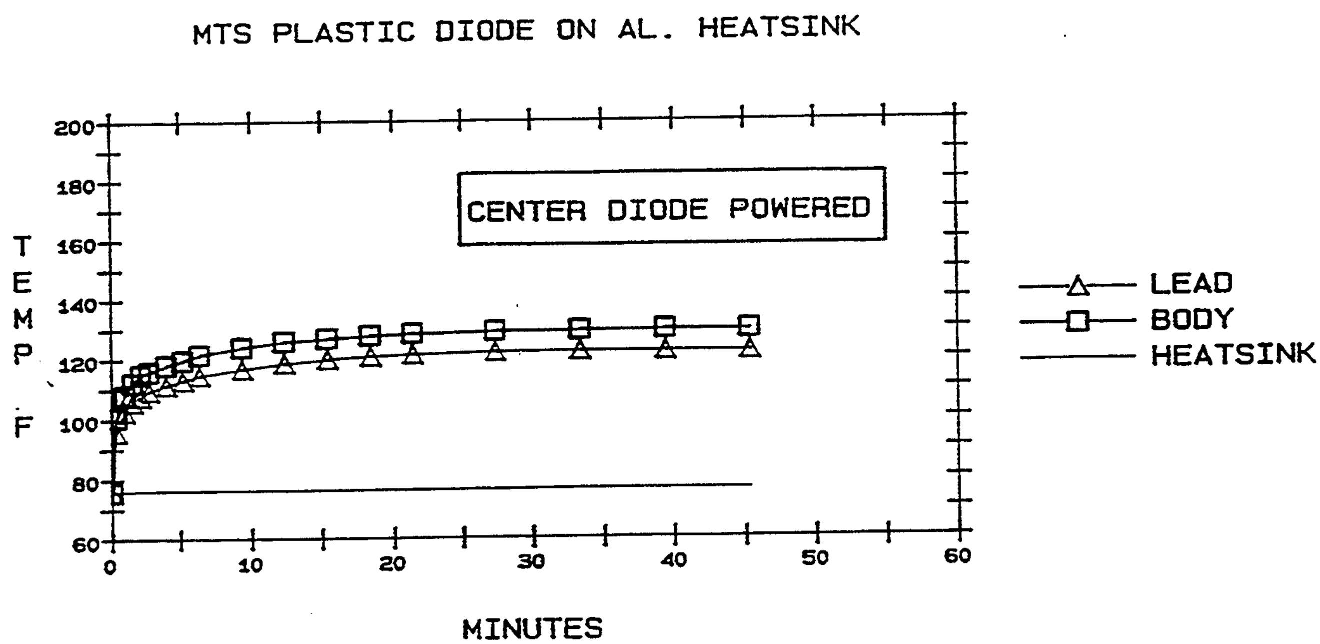


Figure 5. Lead and Body Temperatures for 2 Typical Runs

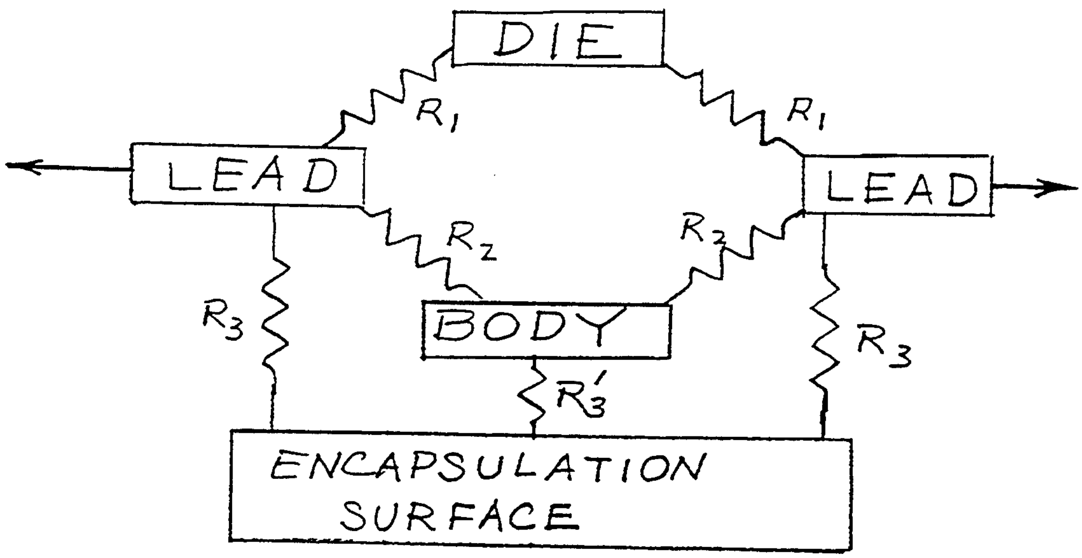


Figure 6.   Thermal Network

If the body temperature rises by T_{B1} when only the center diode is powered, and the corresponding rise is T_{B3} when all diodes are powered, we can then write:

$$F = \frac{Q_{Body}}{Q_{Total}} = \frac{T_{B1}}{T_{B3}}$$

Reference to Table 1 will show that only one matched pair of runs (T2 and T3A) is available for plastic diodes. These give a ratio of 29.1/48.0 = 61% for the heat conducted out the diode case.

Similarly, two matched pairs are available for glass diodes (T1, T2A and T2B, T3). These give 60% and 64%, respectively, for the fraction conducted out the case.

PROPOSED METHOD FOR IMPROVED MEASUREMENTS

An improved experiment would be to have two thermocouples on the lead, separated by a measured distance. Since the lead has a known high thermal conductivity, it is easy to compute its thermal resistance. From the temperature difference between thermocouples, the heat flow down the lead can be computed, and the heat flow from the body determined as the difference from the total power dissipation in the diode.

Thermal imaging using infrared thermography also offers a way to get detailed temperature information economically. (In contrast, the thermocouple measurements recorded temperatures only at 3 points.) If the epoxy block were to be split into two halves, exposing the diodes at the interface, then it could be opened after reaching a steady state and the whole temperature distribution on the interface quickly recorded. Temperature gradients in the epoxy could then be measured directly.

This split block approach presents some fabrication challenges. Another option would be to construct a similar test structure to the one used here but with one thermal path to the exterior surface reduced to a dimension slightly greater than the diode case radius. This surface would then be thermally imaged as a function of time, thus establishing temperature differences needed for calculating heat transfer values for the leads and cases.

TABLE 1. TEST DATA FOR PLASTIC AND GLASS DIODES

Type	Run No.	Date	No. of Diodes	T_{Body} for 30 min Temp Rise		Heat Sink (+/-)	Encapsulant (Full/Reduced)
				µv	°C		
P	T1a	11/8/91	1	1180	28.8	-	F
P	T1b	11/11	1	1290	31.5	-	F
P	T2	11/12	3	1970	48.0	+	F
P	T3a	11/12 am	1	1195	29.1	+	F
P	T3b	11/12 pm	1	1180	28.8	+	F
P	T4	12/12	3	2175	53.0	-	R
P	T5a	12/9	3	1525	37.2	+	R
P	T5b	12/10	3	1523	37.1	+	R
G	T1	11/14	1	1590	38.8	-	F
G	T2a	11/14	3	2470	60.2	+	F
G	T2b	11/14	3	2400	58.5	+	F
G	T3	11/14	1	1430	34.9	+	F
G	T4	12/10	3	2700	65.8	-	R
G	T5	12/12	3	2000	48.8	+	R

2.6 Electrical, Mechanical And Thermal Properties Of Specific Encapsulants

A principal objective of these characterization studies is to provide a common baseline for the properties of each material. Such commonality does not generally exist because different vendors, and laboratories, use different methods and conditions to characterize materials. Reported material property values are often dependent upon these methods and conditions. We have analyzed commonly used materials from several vendors by the same methods and under the same test conditions so that they may be directly compared.

TASK OVERVIEW:

To achieve the study objective, the following tasks were conducted:

(1) identify the needed properties of potting materials to insure reliable HVPS performance,

(2) select appropriate encapsulants (and their sources),

(3) identify test methods which quantified these properties, and

(4) test the proposed materials in order to provide data necessary for the proper selection of potting materials for a given application.

IDEALIZED ENCAPSULANT PROPERTIES:

Since there is neither one universal HVPS nor an ideal encapsulant suitable for different HVPS's, the first activity performed under this task was to derive general material requirements for the demonstration HVPS assembly, namely: the epoxy encapsulated AMRAAM A-3 module. Table 1 lists the material properties, which engineers usually desire to see in high voltage encapsulants. From this myriad of desired properties, the pertinent general material requirements for the A-3 module are: high voltage capability, high heat transfer function, low electrical loss, adherence to the surfaces of both the components and construction materials, mechanical adequacy, processability and repairability. While the order and magnitude of importance of each of these characteristics will vary depending on the individual HVPS design, these requirements are generally germane for most HVPS assemblies.

CURRENT POTTING COMPOUNDS:

The current A-3 module is an epoxy-encapsulated HVPS, actually comprised of different potting compounds for different purposes. Table 2 provides a breakdown of the potting components, potting compounds, areas of use and problems encountered with these materials. Note that alumina or silica filler is used as part of the pottant for the purpose of minimizing CTE and maximizing thermal conductivity.

POTTING COMPOUNDS SELECTED FOR COMPARISON:

Epon 825/HV and Scotchcast 280, the two primary potting materials employed in this HVPS, served as the baseline encapsulants for the materials task. An additional 15 candidate potting materials were selected for review based on initial assessments of their ability to satisfy one or more of the aforementioned general material requirements. Table 3 lists the resulting seventeen encapsulants, material type and sources of supply. Table 4 categorizes these encapsulants based on the initial characteristic assessments. Three of the seventeen encapsulants were not evaluated. DA3C, a Hughes formulation employing a novel epoxy resin, was eliminated from consideration when FIC chemicals, the resin supplier, was no longer willing to import it from Japan. Araldite CY225 and Envibar UV 1244T were only obtained towards the end of the materials task. Consequently, they were not evaluated due to time and

Table 1 – Desirable Material Properties for High Voltage Encapsulants

Category	Property
Electrical	High Corona Inception Levels High Dielectric Strength Low Conductivity (high resistivity) Low Dissipation Factor Low Dielectric Constant
Mechanical	High Strength Low Modulus Good Adhesion tO Substrates High Impact Resistance
Thermal	High Thermal Conductivity Low CTE Good Thermal Stability
Physical	Good Dimensional Stability Low Outgassing Low Density
Chemical	Low Water Absorption/transmission Good Chemical Resistance Good Weather Resistance
Processing	Low Viscosity Long Pot-life Minimal Cure Shrinkage Low Cure Temperature
Repairability	Low Modulus Remaining Material not Degraded

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Table 2 – Current AMRAAM A3

Material		Area of Use	Function	Problems
Scotchcast 280 + Al_2O_3 Filler		Tertiary Encapsulation For Converter	Shock Resistance, Minimize CTE Mismatch	Pot-Life; Cracking
Epon 825 / HV		Transformer		
Epon 825 / HV or Epon 825 / 871 / Menthane diamine or Epon 825 / 871 / HV or Scotchcast 280	with SIO_2 or Al_2O_3	Network Capacitor / Resistor		
Epon 825 / HV or Epon 825 / 871 Methane diamine or Epon 825 / 871 HV or Scotchcast 280		Rectifier Collector Rectifier Cathode		

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Table 3 – Candidate Encapsulants

Material	Type	Source
Epon 825/HV	Unfilled epoxy/amine	Epon 825-Dow Chemical Company Polyurethanes and Epoxy Resin Department Midland, Michigan HV - EV Roberts and Associates, Inc Culver City, California
Scotchcast 280 Scotchcast 281 Scotchcast MR283 F025 Scotchcast MR283 F100	Unfilled epoxy/anhydride Filled epoxy/anhydride Filled epoxy-acrylic/anhydride	3M Company Electrical Products Division Austin, Texas
Uralane 5753	Unfilled polyurethane	Ciba Geigy Corporation Furane Products Division Los Angeles, California
Stycast 2651/Catalyst II Stycast 2850FT/Catalyst II	Filled epoxy/amine	Emerson and Cuming, Inc Woburn, Massachusetts
Ricotuff LV	Unfilled expoxy-butadine/ anhydride	Ricon Resins, Inc. Grand Junction, Colorado
PR 1665	Unfilled polyurethane	Courtaulds Corporation Glendale, California
DA3C HRG-3/AZ HRG-3/AO	Unfilled epoxy/anhydride Unfilled epoxy-silane/amine	Hughes Aircraft Company Electro-Optical Systems Technology Support Division El Segundo, California

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Table 3 – Candidate Encapsulants (Con't)

Material	Type	Source
Araldite CY 9729/HT907/ DY 9741	Unfilled cycloaliphatic epoxy/anhydride	Ciba Geigy Corporation Electrical Power Division Hawthorne, New York
Araldite CY225	Unfilled epoxy/anhydride	
Epotek XK/5022-86	Unfilled epoxy/anhydride	Epoxy Technology, Inc. Bilerica, Massachusetts
Envibar UV1244T	Unfilled UV curing cycloaliphatic epoxy/ anhydride	Union Carbide Chemicals and Plastics Company, Inc. Indianapolis, Indiana

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Table 4 – Initial Characteristics Assessments of Candidate Encapsulant Materials

MATERIAL	FUNCTION AT HIGH ELECTRIC STRESS	HIGH HEAT TRANSFER	LOW ELECTRICAL LOSSES	ADHERENT	PROCESSIBLE	REPAIRABLE	MECHANICAL ADEQUACY
EPON 825/HV	X		X	X	X		X
SCOTCHCAST 280			X	X	X		X
SCOTCHCAST 281		X		X	X		X
SCOTCHCAST MR283 F-025		X	X	X	X		X
SCOTCHCAST MR283 F-100		X		X	X		X
URALANE 5753				X	X	X	X
STYCAST 2651		X		X			X
STYCAST 2850 FT		X		X	X		X
RICOTUFF LV	X		X	X	X		X
PR 1665				X	X	X	X
DA3C	X		X	X	X		X
HRG-3/A2			X	X	X	X	X
HRG-3/A0			X	X	X	X	X
CY 9729/HT907/DY9741	X		X	X	X		X
CY225	X		X	X	X		X
ENVIBAR UV 1244T	X		X	X	X		X
EPO TEK XK/5022-86	X		X	X	X		X

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Table 5 – Processing Parameters

MATERIAL	MIX RATIO (PBW)	CURE SCHEDULE		SPECIAL HANDLING
		TEMPERATURE (°F)+	TIME (HOURS)*	
SCOTCHCAST MR 283 F025	5 TO 1	167	36	WARM PART A AND B SEPARATELY TO NO MORE THAN 140°F HIGH SPEED MIXING 1000-1600 RPM
SCOTCHCAST MR 283 F100	5 TO 1			
SCOTCHCAST 280	2 TO 3	150	24	WARM PART A AND B SEPARATELY TO NO MORE THAN 140°F
SCOTCHCAST 281	2 TO 3			
STYCAST 2850 FT (CATALYST II)	100 TO 8	160	2	NONE
STYCAST 2651 (CATALYST II)	100 TO 8			NONE
EPON 825/HV	100 TO 8	160 250	16 4	DECRYSTALLIZE EPON 825 AT 160°
PR 1665	36 TO 100	75 180	24 16	DECRYSTALLIZE PART A AT 240-260°F, AND PART B AT 120-140°F. COOL BEFORE USING
HRG-3/A0	100 TO 24	160 250	16 4	NO RESIN PRE-HEATING
HRG-3/A2	100 TO 60			
URALANE 5753	10 TO 2	160 200	16 2	NONE
RICOTUFF LV (NO POSTCURE)	200 TO 100 TO 4	160	4	PRE-HEATING PART A AND B AT 160°F BEFORE MIXING WITH PART C
RICOTUFF LV (POSTCURED)	200 TO 100 TO 4	160 212	4 1	
EPOTEK XK/5022-86	100 TO 200	75 302	24 2	NONE
ARALDITE CY9729/HT907/DY9741	100 TO 74 TO 3	320	4	PRE-HEAT CY9729 AT 160°F BEFORE MIXING HT907 AND DY9741

NOTE: Unless otherwise noted, processing procedure consisted of mixing part A and part B by hand until homogeneous. Pre-heat the mixture at 160°F, degass and pour in pre-heated mold (~160°F).

+Tolerance = ±3°F
*Tolerance = ±5 min for cure times ≤4 hrs, ± 15 min for >4 hrs

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Table 6 – Screening Test Hierarchy

Tier 1

Glass transition temperature
Decomposition temperature
Enthalpy
Coefficient of thermal expansion
Volume resistivity
Surface resistivity

Tier 2

Dielectric constant
Dissipation factor
Lapshear strength
T-peel
Izod impact

Tier 3

Dielectric strength
Tensile strength
Tensile modulus
Viscosity
Hardness
Specific gravity

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budgetary constraints.

PROCESSING CONDITIONS FOR SELECTED COMPOUNDS:
The processing parameters used to combine, mix, and cure each of the remaining fourteen encapsulants are listed in Table 5. The mix ratio, cure temperature and time, and any special handling steps are presented. Using these procedures, test specimens were fabricated for the testing program described below.

TESTING PLAN:
The candidate materials were subjected to the screening tests hierarchy shown in Table 6. The testing methodology was designed to accomplish three goals:

(1) to provide data with a common baseline,
(2) to minimize the testing of unworthy candidates, and
(3) to generate sufficient data to allow for candidate screening and selection.

It was not the intent of this task to fully characterize the candidate materials.

A summary of the test methods and conditions selected for use in this task are given in Table 7. All but three of these tests, thermal conductivity, moisture effect and coefficient of thermal expansion (CTE) via dilatometry were performed. The three excluded tests were not run due to budgetary constraints. In order to reduce the cost of screening the numerous candidate materials a small number of replicate coupons per test (i.e., 3 to 8) were fabricated.

RESULTS FROM TIER 1 TESTING:
The final fourteen candidates were subjected to the Tier 1 screening (i.e., specimen preparation and where appropriate analysis of thermal properties and volume and surface resistivities).

Processability: The first screening criteria within Tier 1 was to determine whether (1) either the vendor-recommended or standard-use processing cycle actually produced fully-cured materials and/or whether (2) simple specimens could be fabricated. One candidate was eliminated by this criteria. That is, Araldite CY9729/HD907/DY9741 was eliminated because crack-free specimens could not be fabricated.

Interpretation of Test Results: The Tier 1 test results are presented in Tables 8 through 10. In order to better understand Table 8, a few guidelines are in order and are as follows:

1. The lower the glass transition temperature (Tg), the more rubbery a polymer is at room temperature.

2. The higher the decomposition temperature (Td), the more thermal stability the material possesses.

3. Enthalpy (Δ H) is the measurement of extensive

Table 7 – Test Methods

TEST	DATA	SPECIFICATIONS	SPECIMAN CONFIGURATION	TEST CONDITIONS
THERMAL CONDUCTIVITY	CONDUCTIVITY VALUES	ASTM F433	2 IN. DIAMETER x 1/4 IN. THICK (2 IN. D x 1/4 IN. T)	NOT PERFORMED
COEFFICIENT OF THERMAL EXPANSION	CTE	ASTM E831 (TMA) OR ASTM E83 (DILATOMETER)	1/2 IN. D x 1/4 IN. T	–140 TO 240°C, 5 GRAM LOAD, N_2 1090 DuPONT THERMAL ANALYZER WITH 943 TMA
ENTHALPY	ΔH	ASTM (DSC) D3418	1/2 IN. D x 1/4 IN. T	–100 TO 500°C, 10°C/MIN. N_2 1090 DuPONT THERMAL ANALYZER 910 DSC
GLASS TRANSITION TEMPERATURE	Tg	ASTM (TMA/DSC) D3418	1/2 IN. D x 1/4 IN. T	–140 TO 500°C, N_2 5 GRAM LOAD (TMA); 10°C MIN. (DSC 1090 DuPONT THERMAL ANALYZER WITH 943 TMA AND 910 DSC
VOLUME/SURFACE RESISTIVITIES	OHM-CM 9IN.);OHM/□ AS FUNCT T°C	ASTM D257	4 IN. D x 0.040 IN. T	ROOM TEMPERATURE 500 VOLTS
DIELECTRICAL CONSTANT	DIELECTRICAL CONSTANT AS FUNCTION OF FREQUENCY	ASTM D150 (NO CONDITIONING)	2 IN. D x 0.040 IN. T	ROOM TEMPERATURE 1 VOLT RMS 1 KHz – 1 MHz
DISSIPATION FACTOR	DISSIPATION FACTOR AS FUNCTION OF FREQUENCY		RHEOMETER CS RDS 7700	DC 200 SILICONE OIL USED IN FLUID FILLED CELL OF
TENSILE STRENGTH AND ELONGATION	YIELD AND ULTIMATE STRENGTH/ ELONGATION	ASTM D638	3/4 IN. x 7 IN. x 1/4 IN. DOGBONE	ROOM TEMPERATURE 0.050 IN./MIN. INSTRON UNIVERSAL TESTOR MODEL H25
TENSILE MODULUS	TENSIL MODULI			

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Table 7 – Test Methods (Cont)

TEST	DATA	SPECIFICATIONS	SPECIMAN CONFIGURATION	TEST CONDITIONS
ADHESIVE STRENGTH TO AL, EPOXY AND/OR POLYMIDE GLASS LAMINATE, FUSED Sn/Pb TESTERSOLDER	LAP-SHEAR STRENGTHS	ASTM D1002	1 IN. x 1/2 IN. x 0.005 IN. OVERLAP	ROOM TEMPERATURE 0.050 IN./MIN. INSTRON UNIVERSAL MODEL 1125
T-PEEL	PEEL	ASTM D1876	1 IN. W x 12 IN. L	ROOM TEMPERATURE 0.050 IN./MIN INSTRON UNIVERSAL TESTER MODEL 1125
HARDNESS	SHORE VALUE (INITIAL AND 10 SEC DWELL)	ASTM D2240	HOCKEY PUCK	ROOM TEMPERATURE SHORED A OR SHORE D DUROMETER
SPECIFIC GRAVITY	SPECIFIC GRAVITY VALUE	ASTM D792	ANY	ROOM TEMPERATURE ANALYTICAL BALANCE
MOISTURE EFFECT	EXPOSURE AND RECOVERY	MIL-STD 202 METHOD 106	—	NOT PERFORMED
DIELECTRIC STRENGTH	DIELECTRIC STRENGTH	ASTM D149	2 IN. D	ROOM TEMPERATURE ~500 V/SEC CVE HI-POT MODEL 2402
VISOCITY	VISOCITY	ASTM D2393	≤ 500 ML	ROOM TEMPERATURE AND 160°F, BROOKFIELD RVF VISCOMETER
IZOD IMPACT	IZOD IMPACT	ASTM D256	1/2 x 1/2 x 2 1/2 IN.	ROOM TEMPERATURE INSTRON UNIVERSAL TESTER MODEL 1125

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Table 8 – Glass Transitition and Decomposition Temperatures and Enthalpy Values of Candidate Materials

Material	Tg* (°C)	Td* (°C)	ΔH+ (J/g)
Uralane 5753	-75 to -60	289	0
Ricotuff LV (Postcured)	-60 to 60	290	0
PR 166 65	-43	228	0
Scotchcast MR 283 F100	0 - 45	303	3
HRG-3/42	8 - 12	245	0
HRG/A0 (New)	8 - 10	345	0
HRG-3/40	10 - 12	339	0
Scotchcast 280	30	284	4
Scotchcast 281	46	291	0
Ricotuff LV (No postcure)	48 - 80	248 - 257	14
Scotchcast MR 283 F025	54	307	1
Stycast 2850 ft	65 - 80	299	0
Stycast 2651	96 - 104, 139*	328	0, 5
Epon 825/HV	120 -140	253	0
Epotek XK/5022-86 (postcured)	30	255	14 - 17

*Tolerance = ±5°C

*Tolerance = 1/2 J/g

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Table 9 – Coefficients of Thermal Expansion of Candidate Materials

Materials	CTE Below Tg (PPM/°C)	CTE Above Tg (PPM/°C)
Stycast 2850 ft	20 - 27	76 - 106
Stycast 2651	26 - 34	115 - 122
Scotchcast MR 283 F025	34 - 45	143 - 150
Scotchcast MR 283 F100	37 - 53	139 - 170
Scotchcast 281	39 - 62	154 - 177
Epon 825/HV	41 - 66	171 - 188
Ricotuff LV (No postcure)	56 - 111	173 - 182
Ricotuff LV (Postcured)	58 - 106	150 - 198
HRG-3/A0 (New)	75 - 231	208 - 246
HRG-3/A2	77 - 82	214 - 237
Scotchcast 280	79 - 91	210 - 22 6
HRG-3/A0	91 - 104	213 - 226
PR 1665	92	205 - 211
Uralane 5753	103 - 110	202 - 252

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Table 10 – Volume/Surface Resistivities of Candidate Materials

Materials	Volume* Resistivity (Ω-cm)	Surface* Resistivity ($\Omega/\square$)
PR 1665	1×10^{12}	1×10^{13}
Scotchcast MR 283 F100	8×10^{13}	$\geq \times 10^{14}$
Ricotuff LV (Postcured)	2×10^{14}	9×10^{12}
Scotchcast 280	3×10^{14}	$\geq \times 10^{14}$
Epotek XK/5022-86	5×10^{14}	$\geq \times 10^{14}$
HRG-3/A2	6×10^{14}	$\geq \times 10^{14}$
Ricotuff LV (No postcure)	1×10^{15}	$\geq \times 10^{14}$
Stycast 2850 ft	2×10^{15}	$\geq \times 10^{14}$
Scotchcast 281	3×10^{15}	$\geq \times 10^{14}$
Stycast 2651	4×10^{15}	$\geq \times 10^{14}$
Scotchcast MR 283 F025	6×10^{15}	$\geq \times 10^{14}$
HRG-3/A0	7×10^{15}	$\geq \times 10^{14}$
Uralane 5753	8×10^{15}	$\geq \times 10^{14}$
Epon 825/HV	6×10^{16}	$\geq \times 10^{14}$

*Tolerance = ±50 percent

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cure. A fully-cured material would exhibit a Δ H of zero. A slightly under-cured material may have Δ H values of less than or equal to 5 joules per gram. When Δ H exceeds 10 joules per gram, the materials considered is considered significantly under-cured.

4. A second scan means that during thermal analysis a specimen was heated above Tg, but below Td, cooled to the original testing temperature, and ramped to Td for re-analysis.

A second scan was performed on Stycast 2651 (it was heated to 255°C prior to cooling to -100°C). It can be seen from Table 8, that the postcured Epotek XK/5022-86 and the non-postcured Ricotuff LV were significantly under-cured. Stycast 2651 (initial scan), Scotchcast 280 and Scotchcast MR 283-F100 were just slightly under-cured and as such were retained as candidates. Since postcuring of Ricotuff LV resulted in a fully cured material, it was also retained. However, Epotek XK/5022-86 could not be fully-cured and thus was eliminated from further testing.

Glass Transition Temperature Groupings: The remaining 13 candidate materials can be grouped into three different classes based upon their glass transition temperature - namely: very low, low, and moderate. According to this classification, Uralane 5753, Ricotuff LV (post-cured) and PR 1665 are very low glass transition temperature materials. Ricotuff LV has a very broad glass transition temperature range so that it actually exhibits thermal properties in the regions of very low - to - low - to - moderate thermal behavior. HRG-3/A2 and HRG-3/A0 are both low glass transition temperature materials. Scotchcast MR283-F100, a highly filled material, exhibits low to moderate thermal properties. MR283-F100 does not appear to be ductile and this is due to the high degree of filler in the compound. Such is also the case for Scotchcast 281 and Scotchcast MR283-F025. The HRG-3/A0 and HRG-3/A2 are low glass transition temperature materials that do exhibit ductility. The Ricotuff LV (no postcure), Scotchcast 280 and Stycast 2850-FT are approaching the moderate temperature range. Stycast 2651 and Epon 825/HV are moderate temperature materials. The last two groups exhibit rigidity as opposed to ductility at ambient temperature.

Decomposition Temperatures: All of the candidate encapsulants possess high decomposition temperatures (Td's) relative to the low temperatures at which the HVPS assemblies operate. All of these materials would be viable based upon decomposition temperature. Selections based on glass transition temperature would be a function of the operating range of the HVPS in question.

Coefficient of Thermal Expansion: Extensive industry problems have occurred when the operating range of the HVPS brackets the glass transition temperature range of its encapsulant. Since glass transition temperature is the period of rapid change in the polymer both physically and mechanically, operation of the HVPS in this critical region can result in encapsulant cracking as well as electrical and other property degradation. Cracking of the encapsulant can be explained by the thermomechanical stresses induced by temperature change and by the huge jump in coefficient of thermal expansion that occurs when the polymer goes from the rubbery to the glassy region. Table 9 lists the CTE's of the candidate materials. It can be seen that the more rigid materials have a very low thermal coefficient of expansion below Tg. In all cases above Tg, the rubbery region, polymers have very high coefficients of thermal expansion.

<u>Resistivity:</u> Table 9 also lists the volume and surface resistivities of the candidate materials. All of the candidate materials are non-conductors having volume resistivities in excess of 10^{12} ohm-cm and surface resistivities in excess of 10^{12} ohms/square.

<u>RESULTS FROM TIER 2 TESTING:</u>
Twelve materials were selected for Tier 2 testing Scotchcast 281, Scotchcast 280, Ricotuff LV (cured and post-cured), HRG-3/A0, Uralane 5753, HRG-3/A2, Scotchcast MR283-F025, Scotchcast MR283-F100, Epon 825/HV, PR-1665 and Stycast 2850-FT.

<u>Dielectric Constant and Dissipation Factor:</u> Table 11 and 12 list the dielectric constant and dissipation factors of the candidate materials. The dielectric constant of an encapsulation material is important, in that the maximum operating frequency at which an analog circuit can be operated, and the speed at which a digital circuit can be operated, depends upon the dielectric constant of the materials adjacent to it. Higher frequency analog circuitry requires higher dielectric constant encapsulants (and printed wiring board materials). Higher speed digital electronics requires lower dielectric constant encapsulants (and printed wiring board materials). Dissipation factor in an encapsulant is an indication of the amount of heat that is generated when the encapsulant is in the presence of electric fields that surround circuitry. Examination of Table 11 shows that none of the materials have low dielectric constants, where low is considered to be less than three (3.0). PR-1665 is definitely a high dielectric constant material as it possesses a dielectric constant in excess of 7.0 (at one KHz). Generally when a material possesses a high dielectric constant it also exhibits a high dissipation factor. This is the case for the PR-1665. Its dissipation factor ranges from 0.028 at 10 KHz to 0.053 at 1 MHz.

<u>Candidate Pruning:</u> Due to its high dissipation factor, PR-1665 was eliminated from further Tier 2 testing. Since Scotchcast MR283-F025 possessed lower dissipation factors and dielectric constants than the MR283-F100, the F025 was retained, but the F100 version was eliminated from Tier 3 testing. Dissipation factor was also the key property that eliminated the non-postcured Ricotuff LV from additional testing. The post-cured Ricotuff LV exhibited the lowest dissipation factor of the dozen candidates in Tier 2 testing.

Table 11 – Dielectric Constants of Candidate Materials

Material	Dielectric Constants Frequency (K Hz)			
	1	10	100	1000
Scotchcast 281	4.10	3.68	3.44	2.20
Scotchcast 280	3.14	3.02	3.94	2.87
Ricotuff LV (No postcure)	3.12	3.04	2.96	2.88
HRG-3/AO	3.39	3.17	3.02	2.91
Uralane 5753	3.44	3.34	3.21	3.10
Ricotuff LV (Postcured)	3.28	3.23	3.18	3.12
HRG-3/A2	3.98	3.62	3.42	3.30
Scotchcast MR 283 F025	3.61	3.54	3.47	3.40
Scotchcast MR 283 F100	4.12	3.93	3.74	3.55
Epon 825/HV	4.61	4.50	4.36	4.19
PR 1665	7.14	6.45	5.86	5.21
Stycast 2850 ft	6.44	6.34	6.18	6.01

*Tolerance = ±0.2

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Table 12 – Dissipation Factors of Candidate Materials

	Dissipation Factor		
	Frequency (K Hz)		
Materials	10	100	1000
Rocotuff LV (Postcured)	0.0053	0.0068	0.0090
Scotchcast MR 283 F025	0.0071	0.0083	0.0097
Stycast 2850 ft	0.0080	0.0120	0.0160
Ricotuff LV (No postcure)	0.0096	0.0104	0.0104
Epon 825/HV	0.0105	0.0154	0.0189
Scotchcast 280	0.0110	0.0097	0.0100
Uralane 5753	0.0170	0.0180	0.0170
HRG-3/AO	0.0210	0.0170	0.0140
Scotchcast MR 283 F100	0.0245	0.0205	0.0201
PR 1665	0.0281	0.0505	0.0530
HRG-3/A2	0.0300	0.0180	0.0140
Scotchcast 281	0.0336	0.0207	0.0137

*Tolerance = ±0.001

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Mechanical Properties: Table 13 gives the mechanical test results of the candidate materials. Ricotuff LV possessed exceptionally low T-peel strength when it was non-postcured. Postcuring this material increased its T-peel from unacceptable to the low range exhibited by the brittle Epon 825/HV, Stycast 2850-FT, Scotchcast 281, Stycast 2651, and the two Scotchcast MR283-F100, and MR283-F025. The latter two materials exhibit a little more ductility having T-peels between 6 and nearly 8 pounds per inch width. The remaining five materials exhibit very good T-peel values ranging from 14 to nearly 31 pounds per inch width. As expected they possess lower lap shear strengths than the former materials. As another measure of ductility, Izod impact was performed. It was surprising that only four materials exhibited excellent impact resistance. Scotchcast MR283-F100 and MR283-F025, despite having moderate T peel values, had Izod impact values comparable to the much more ductile HRG-3/A0 and Scotchcast 280.

RESULTS FROM TIER 3 TESTING:

The remaining nine candidates were tested to the Tier 3 agenda of dielectric strength, tensile strength, modulus, and elongation, viscosity, hardness, and specific gravity.

Dielectric Strength: Just as dissipation factor is a measure of a material's electrical loss, and thermal conductivity gives an indication of its heat transfer function, so dielectric strength is a parameter with which one can gauge a material's suitability for high voltage applications. The dielectric strength values of the remaining candidates are given in Table 14. Ricotuff LV exhibited the highest dielectric strength (i.e., 1256 volts/mil). Epon 825/HV, a high voltage encapsulant widely used by Hughes, was a very close second at 1190 volts/mil. HRG-3/A0, a very ductile material, also possessed a very high dielectric strength and was third best. This is somewhat unusual since ductile materials generally are not high voltage carrying materials. In spite of being undercured, Epotek XK/5022-86 possessed a very acceptable dielectric strength of nearly a thousand volts/mil. Scotchcast 280, also widely used by Hughes for power supply encapsulation, has a lower dielectric strength value of 870 volts/mil.

Tensile Properties: Table 15 gives the tensile strength, modulus and elongation values of the Tier 3 candidate materials. As was seen in the cases of T-peel and lap shear values, the stronger the material, the less ductile it generally is. The very ductile Uralane 5753 and HRG-3/A0 materials both have elongation values of approximately 200% and tensile strengths and moduli of less than 1 ksi. Scotchcast 280 is a semi-rigid epoxy as indicated by its combination of moderate tensile strength (1.8 ksi), moderate modulus (21.8 ksi) and high elongation (119%). The unfilled urethane, PR-1665, had extremely high elongation 536%. However, it had been previously eliminated due to its unacceptable dielectric properties. As expected with the more rigid materials, ultimate elongations are less than 10%. The very high modulus compounds, Scotchcast MR283-F025 and Stycast 2850 FT, have the lowest elongations (less than 1%) as might be expected with such rigid materials.

Viscosity: Table 16 lists the viscosity, hardness and specific gravity of the surviving

Table 13 – T-Peel, Lap Shear, and Izod Impact Strengths of Candidate Materials

Material	Strength		
	T-Peel (PIW)	Lapshear (KSI)	Izod Impact [(Ft-lb)/in.]
Ricotuff LV (postcured)	<1	2.72 ± 0.07	3.4
Epon 825/HV	2.3 ± 0.04	2.00 ± 0.71	3.4
Ricotuff LV (nopostcured)	2.4 ± 0.1	2.80 ± 0.32	
Stycast 2850 FT	3.7 ± 0.6	2.63 ± 0.07	3.0
Scotchcast 281	5.2 ± 0.6	2.45 ± 0.80	3.2
Stycast 2651	5.9 ± 0.5	2.80 ± 0.08	2.9
Scotchcast MR 283 F100	6.1 ± 1.3	2.01 ± 0.35	7.2
Scotchcast MR 283 F025	7.9 ± 5.9	3.37 ± 0.03	7.2
Uralane 5753	14.2 ± 2.5	0.72 ± 0.24	1.3
HRG-3/A0	16.7 ± 0.7	1.08 ± 0.01	7.6
PR 1665	21.5 ± 1.0	0.96 ± 0.24	3.8
HRG-3/A2	22.3 ± 1.4	1.48 ± 0.12	
Scotchcast 280	30.6 ± 1.5	1.45 ± 0.14	≥8.0

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Table 14 – Dielectric Strength – AC

Materials	Dielectric Strength Volts/MIL
Ricotuff LV	1256
Epon 825/HV	1190
HRG-3/A0	1100
Scotchcast 283 F025	1050
Epotek XK/5022-86	995
Uralane 5753	990
Scotchcast 281	960
Stycast 2850 ft	873
Scotchcast 280	870

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Table 15 – Tensile Strength, Tensile Modulus, and Elongation Values of Candidate Materials

Material	Tensile Strength (KSI)	Tensile Modulus (KSI)	Elongation %
Uralane 5753	0.34 ± 0.03	0.55 ± 0.19	207 ± 32
HRG-3/A0	0.51 ± 0.06	0.76 ± 0.34	190 ± 15
Scotchcast 280	1.8 ± 0.18	21.8 ± 12.3	119 ± 16.5
PR 1665	1.95 ± 0.44	3.37 ± 0.09	536 ± 60
Scotchcast 281	2.40 ± 0.01	268 ± 35.8	19.8 ± 1.7
Ricotuff LV (no postcure)	2.62 ± 0.07	117 ± 5.1	6.1 ± 1.5
Scotchcast MR 283 F100	2.76 ± 0.27	162 ± 22	8.2 ± 1.3
Ricotuff LV (postcured)	2.90 ± 0.41	132 ± 14	3.3 ± 0.9
Scotchcast MR 283 F025	7.1 ± 0.77	1360 ± 48.8	0.61 ± 0.07
Stycast 2850 ft	8.21 ± 1.34	1735 ± 144	0.50 ± 0.20
Epon 825/HV	8.50 ± 2.50	469 ± 63	2.4 ± 0.5

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Table 16 – Viscosity, Hardness and Special Gravity

Material	Viscosity (Centipoises)	Hardness (Shore) Hardness	Specific Gravity
HRG-3/A0	68	64 shore A	1.02
Uralane 5753	4,590	62 shore A	1.09
Epon 825/HV	896	81 shore D	1.18
Ricotuff LV (postcured)	35,400	75 shore D	1.10
Scotchcast 280	5,970	63 shore D	1.49
Scotchcast 281	88,200	70 shore D	1.42
Stycast 2850 FT	40,800	94 shore D	2.31
Scotchcast MR 283 F025	10,220	88 shore D	1.40

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Tier 3 candidates. Low viscosity is important for high voltage potting because voids must be eliminated as they can be a source of electrical breakdown. HRG-3/A0 is an extremely low viscosity material, having an ambient temperature of viscosity of 68 centipoise (cp). Uralane 5753 and Scotchcast 280 are in the moderate viscosity range (circa 5000 cp). Epon 825/HV is also considered a moderately low viscosity it being nearly 900 centipoise. It is common practice to heat this material before encapsulating a device with it. The order of magnitude difference in viscosity between the Epon 825/HV and HRG-3/A0 would appear to indicate that this preheating would not be necessary for the latter material. The three filled materials, Scotchcast 281, Stycast 2850 FT and Scotchcast MR283-F025 have very high viscosities for encapsulants.

Hardness: The two soft materials, HRG-3/A0 and Uralane 5753, have the lowest hardnesses being on the Shore A scale. The Shore A scale is lower in hardness than is the Shore D scale. The remaining materials were significantly harder being on the high end of the Shore D scale. Scotchcast is the lowest of the "D" scale materials and indeed is a semi-rigid epoxy. The hardest compound was Stycast 2850 FT at 94 Shore D. This is actually the limit of the instrument. Readings between 95 and 100 are not meaningful. The high filler loading in Stycast 2850 FT is responsible for the high hardness.

Specific Gravity: The specific gravity values of the candidate materials range from slightly over 1.0 for HRG-3/A0 to 2.31 for the filled compound, Stycast 2850 FT.

Pot Life and Gellation: Table 17 shows viscosity as a function of time at 160°F. This temperature was chosen as our standard pre-heating temperature used during the encapsulation process. The usefulness of this table is that it allows one to select a potting compound which has sufficient work life for the application. One of the most severe applications is the potting impregnation of a particulate-filled cavity or fabric-wound device. Low viscosity and long work life are then needed to penetrate the filler or fabric. It can be seen in Table 17 that Uralane 5753 has an exceptionally short pot life since it gelled within half an hour. Stycast 2850 FT gelled within less than 1 1/2 hours, whereas Epon 825/HV gelled in less than 2 1/2 hours. HRG-3/AO, which started at a very low viscosity, was still processable after 5 1/2 hours despite increasing in viscosity nearly 1 1/2 orders of magnitude. These data are presented graphically in Figure 1. This graph is a useful guide that helps one assess the length of time one has to work with each of the materials shown, after those materials have been prepared for encapsulation. For example, if one wished to use EPON 825/HV, and the encapsulation application permitted use of a material with a viscosity as high as 4000 PCPs, the chart indicates that the working life of the material is about one hour. As a second example, when impregnating a volume that has been filled with dry powder particles such as alumina, one needs to use a material with a relatively low viscosity. From the figure, it is apparent that Scotchcast 280 and HRG-3/AO would be quite suitable from this point of view. These materials offer a working life of at least several hours in that application.

Table 17 – Viscosity as a Function of Time At 160°F

	Viscosity at 160°F (centipoises)					
Material	0.5 HR	1.5 HRS	2.5 HRS	3.5 HRS	4.5 HRS	5.5 HRS
Uralane 5753	Gelled	Gelled				
Epon 825/HV	420	7470	Gelled			
Ricotuff LV	1900	2800	4180	6680	Gelled	
Scotchcast 280	120	240	340	420	550	680
Scotchcast 281	2100	2640	3320	4190	5280	6500
Stycast 2850 FT	4000	Gelled				
Scotchcast 283 F025	1060	4680	4920	5720	6520	10920
HRG-3/A0	35	48	66	126	223	1120

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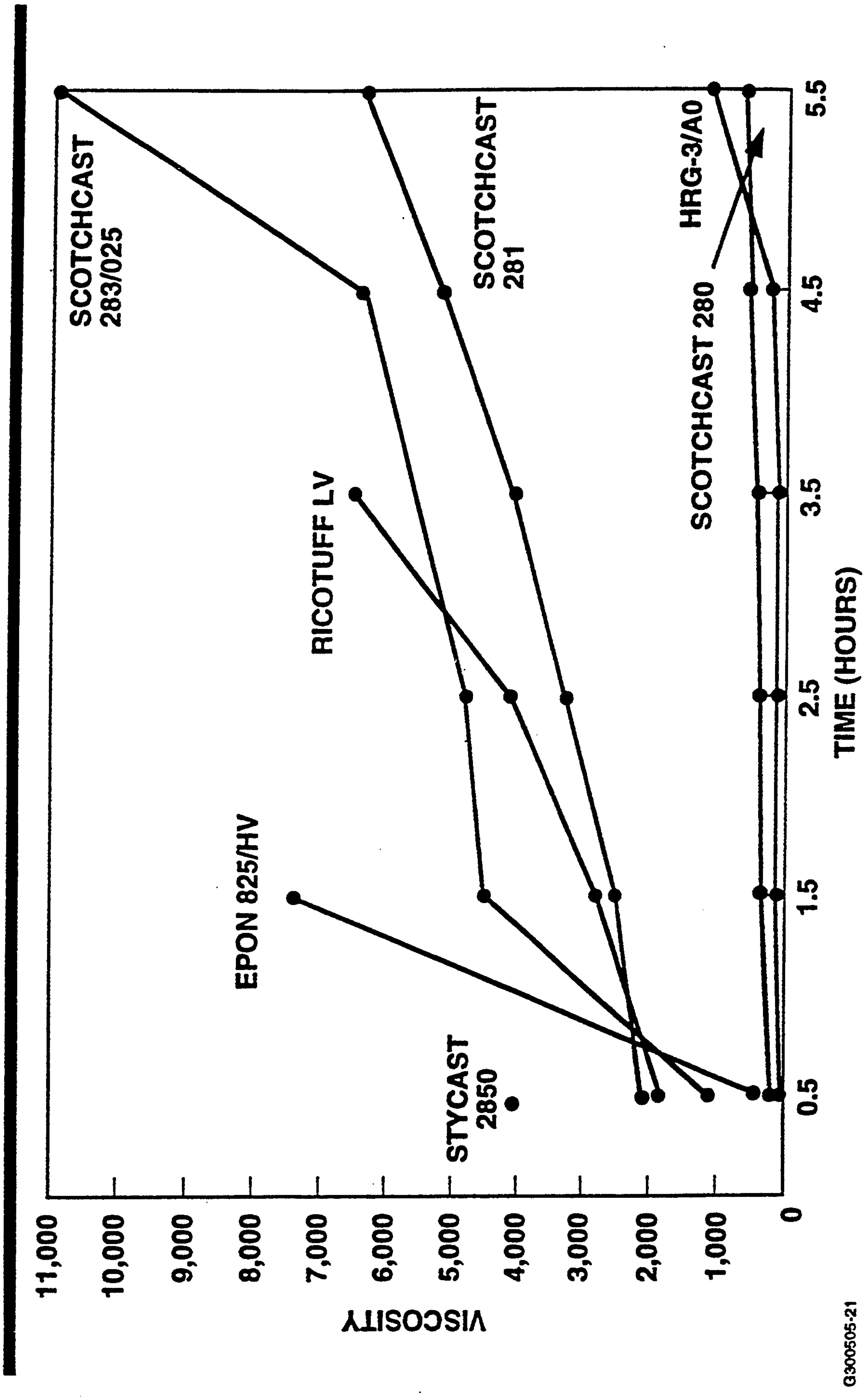
Figure 1 – Viscosity Versus Time



DESIGN AND MANUFACTURING GUIDELINES

FOR HIGH VOLTAGE POWER SUPPLIES

APPENDIX 4-1

PRIMARY TRANSFORMER TEST STRUCTURE

Section A. Test Transformer Fabrication

QTY		FIND NO.	PART NUMBER	DESCRIPTION
1	EA	1	300-040170-001	TERMINAL BOARD (COIL FORM)
	AR	2	034-001065	ADHESIVE, EPOXY (2216)
60	IN	3	087-011752-003	WIRE, ELECTRICAL (100X36 LITZ)
	AR	4	033-001143-848	SOLDER, TIN ALLOY
5	IN	5	087-012397-024	PLASTIC SHEET, ALTERED
4	IN	6	033-001464-002	INSULATION TAPE, ELECTRICAL
4	IN	7	076-007444-004	STRAP, COPPER, CONDUCTOR
3	IN	8	087-006664-026	WIRE ELECTRICAL, (AWG 26)
10	IN	9	033-002376-019	INSULATION TAPE, ELECTRICAL
	AR	10	034-004002-001	ADHESIVE (UV)
	AR	11	034-000718	INSULATION COMPOUND, ELECTRICAL
1300	IN	12	087-012389-021	WIRE, ELECTRICAL, MAGNET, (K2-34)
12	IN	13	008-013913-004	INSULATION SHEET, ELECTRICAL
10	IN	14	033-001464-011	INSULATION TAPE, ELECTRICAL
	AR	15	034-000648	INSULATION COMPOUND, ELECTRICAL
1	EA	16	077-004818	CORE
18	IN	17	076-005935	STRAP, RETAINING
1	EA	18	076-005933-001	RETAINER, STRAP

1.0 GENERAL REQUIREMENTS.

1.1 The requirements for this transformer shall be as specified by type TF5V03ZZ of MIL-T-27, Northrop DSD specification 050-005194-001 and the requirements herein. This specification is to be used as the building instructions for a 40 kilohertz high voltage step-up power transformer to be used as a method of processing test transformer

2.0 CONSTRUCTION REQUIREMENTS. This transformer will be constructed in two stages, a cast primary and shield assembly followed with a secondary assembly that is to be overcasted. Refer to the schematic diagram, figure 1 and the winding diagram, figure 2.

2.1 Coil Form. Assemble the coil form, find number 1, together using adhesive, find number 2, mixed as directed. After the adhesive has cured, fully grit blast the bobbin surface. The terminals on the flanges are to be masked during the grit blasting operation.

2.2 Primary. The primary is to be wound on the fully grit blasted coil form assembly. The primary is to be 38 turns of magnet wire, find number 3, wound in two tightly wound layers. To start, the lead wire is to be stripped and tinned about two inches using solder, find number 4. Thread the stripped and tinned wire through the primary START terminal. The wire is set when the tinned wire is just in line with the inside of the flange wall. Use a piece of electrical tape, find number 6, to anchor the START of the winding in place as shown in figure 3. The first turn of the winding should be about one wire width away from the bobbin assembly flange wall. Wind on 38 turns in two layers with a single over lapping layer of altered plastic sheet, find number 5, for layer insulation.

2.3 Electrostatic shield. Prepare a strap assembly as shown in figure 8. This tape and strap assembly will be used for the electrostatic shield and final wrapper for the primary. Attach a 2 to 3 inch long piece of lead wire, find number 8, to a 3 to 3.25 inch long piece of copper strap conductor, find number 7, using solder, find number 4, as shown in figure 8. Position the copper strap .5 to 1 inch from the end of a 9 to 10 inch long piece of electrical insulation tape, find number 9. Tack the copper strap to the insulation tape in the area specified in figure 8 using (UV) adhesive, find number 10. Cure the adhesive with an UV source. Position and center the shield and wrapper assembly on to the primary windings so the shield lead wire is aligned and through the shield terminal. Tack the start of the insulation tape directly on to the primary winding, in two places with the UV adhesive and cure, as shown in figure 4. Tightly wrap the coil with the full length of the wrapper and tack the end down with the UV adhesive.

2.4 Primary and shield casting. The primary assembly is to be placed in a mold that will cast the OD of the assembly to 1.25 inches. The assembly is to be cast with insulation compound, find number 11. Clean the coil with the spray wand in the freon degreaser. Cleaning time in the degreaser should be less than 30 seconds. Place the clean coil assembly in a 100 °C vacuum oven for a minimum of two hours at a vacuum of 5 to 10 mm of mercury. The part is to be potted within 24 hours after cleaning and is to be stored in a nitrogen filled dry box until it is to be made ready for casting. Prepare the mold and assemble it around the coil assembly. Place the assembly and the mold into a 65 °C oven to preheat for 60 minutes minimum. Preheat the insulating compound in a 65 °C oven for 60 to 75 minutes in its original container with the lid slightly open. Unscrew the lid on the catalyst but do not remove it. Place the catalyst into a 65 °C for 60 minutes to dissolve any crystals. Remove the coil mold from the 65 °C oven and place into the Red Point vacuum pressure chamber, which has been pre-heated to 65 °C. Pull a vacuum of 5mm of mercury for a minimum of 10 minutes. Slowly pour a mixed deaerated compound into the mold and pull a vacuum of 5mm of mercury for a minimum of 5 minutes. After the five minutes, top off the mold with more compound and then hold the assembly under vacuum for an additional 10 minutes. The chamber is then pressurized with nitrogen gas at 95 to 100 psi for initial cure for 17 to 19 hours. Remove the pressure and cure the assembly for an additional 31 to 33 more hours. Remove the part from the mold and place it into a 100 °C oven for 12 hours minimum. The assembly is now to be post cured in an oven set for 125 °C for eight hours minimum. Let the parts cool to room temperature and remove the risers and file the riser area flush with the outer diameter of the coil assembly. Remove all traces of flashing from the casting. The coil assembly is now ready to be cleaned of any foreign materials such as masking materials and mold release. The primary coil assembly is now to be fully grit blasted.

2.5 Secondary Windings. The secondary windings are to be wound on the fully grit blasted primary assembly. This test transformer is to have two identical single layer solenoid secondary windings. These secondary windings are to start from the same end and are to be 152 turns of magnet wire, find number 12, tightly wound onto the primary assembly. Both windings are to be centered onto the coil form so there are equal margins on both ends. The STARTS and FINISHES of the secondary windings are to be anchored in line with their respective pin numbers using adhesive, find number 10. Cure the adhesive with an UV source. The natural lead STARTS of the secondaries are to be stripped and tinned about 2 inches. The START of secondary 1 is threaded into the terminal designated as Secondary 1 Start in figure 5. The tinned portion of the lead is to slide all the way into the terminal up to the insulation. Anchor the natural lead where it will have an approximate 0.2 inch margin from the inside of the bobbin flange. Tightly level wind 152 turns. Temporarily hold the end of the winding in place so that the natural FINISH lead can be stripped and tinned. The FINISH is to be anchored in the same manner as the START. Wrap the winding with slightly more than three complete layers giving an overlap of approximately 0.25 inches of electrical sheet insulation, find number 13. The wrapper may temporarily be held in place with a small piece of electrical insulation tape, find number 6. If temporary tape is used to hold the wrapper, it must be removed before the next winding is completed. Secondary 2 is to be wound in the same manner as secondary 1. Wrap the coil with two complete layers of electrical insulation tape, find number 14, centered on the winding. Seal the end of the tape in two areas with UV adhesive, find number 10.

2.6 Secondary Lead Soldering. All the secondary leads are to be soldered to their respective pins in the following manner. Form stress reliefs in all the natural leads between the winding insulation and the coil form's flanges. The stress relief on each winding is to be formed in the margin in line with the plane of the winding, not towards the center or outside of the coil. Solder the natural leads in the pins with care to insure that all pins are filled with solder. Solder flux is to be used sparingly. Clean the assembly making sure all excess solder flux residue has been removed. Clip off the excess lead flush with the end of the terminal pin.

2.7 Casting Instruction. Prior to casting, the wound coil assembly is to be cleaned in the freon degreaser with the spray wand. The cleaned winding assembly is to be placed in a 100 °C vacuum oven and baked out for a minimum of two hours at a vacuum of 10mm maximum of mercury. Within the same day of cleaning and vacuum bake, the assembly is to be placed in a mold that the finish casting will meet all the dimensions specified in 050-005194. Seal the mold so that the assembly can be cast. Place the mold with the winding assembly into a 65 °C oven to preheat for 60 minutes minimum. Pull a vacuum of 5mm of mercury for a minimum of 1.5 hours before slowly pouring a 65 °C pre-mixed deairated electrical insulating compound, find number 15, into the mold. Hold the assembly and the mold under a vacuum of 5mm of mercury, or less, for 5 minutes before topping off the mode. Continue the vacuum for 10 minutes. Release the vacuum and pressurize the chamber with nitrogen gas at 95 to 100 psi. Maintain the pressure and cure the assembly for 17 to 19 hour with the chamber set at 65 °C. The coil is left in the mold and further cured for 5 to 7 hours in a conventional oven at 65 °C. Total time for curing in the mold is a minimum of 24 hours.

Remove the coil assembly from the mold and post cure for 24 hours in a 65 °C conventional oven. After the post cure, place the assembly into a 100 °C oven for a 12 to 20 hour cure followed by a final post cure of 8 to 20 hours at 125 °C. The potting surface shall not contain more that one void. No exposed wire shall be visible within the void. Cut off the riser and clean the assembly.

2.8 Core Assembly. Assemble core halves, find number 16, onto the coil assembly. Care is to be taken to insure that no foreign material is trapped between the core pole faces. Band the perimeter of the core with retaining strap and strap retainer, find numbers 17 and 18, at 60 pounds tension and secure the assembly using solder, find number 4. At this time the transformer primary inductance should be checked per paragraph 3.1 to insure proper care alignment.

3.0 ELECTRICAL REQUIREMENTS (reference only). The completed part is to be tested to meet the requirements of Northrop DSD 050-005194-.001.

3.1 Minimum Inductance. The inductance of the primary when measured on a Wayne Kerr Precision Inductance Analyzer model 3245, or equivalent, at 40 kilohertz shall be greater than 3 milli-henries.

3.2 Leakage Inductance. The inductance measured across the primary when measured on a Wayne Kerr Precision Inductance Analyzer model 3245, or equivalent, at 40 kilohertz shall be less than 30 microhenries with the secondaries shorted.

3.2 Maximum DC Resistance. The DC resistance of the windings shall be measured on a resistance bridge using Kelvin connections. The maximum primary resistance shall not exceed 60 milliohms. The maximum resistance of the two secondaries connected in series shall not exceed 28 ohms.

3.3 Electrostatic Shield. With the transformer connected as shown in MIL-T-27 electrostatic-shielding circuit, the detector voltage shall be recorded with the switch open and 100 volts, 400 hertz applied as the source. The detector voltage is then recorded with the switch closed. The ratio of the open switch reading to the closed switch reading shall be greater than 3.

3.4 Turns Ratio. The no-load turns ratio of primary to secondaries shall be within 2 percent of 1 : 4 : 4.

3.5 Dielectric Withstanding Voltage. The transformer shall withstand 10000 volts RMS secondary to primary, core and shield. 500 volts RMS primary to shield and core and 500 volts shield to core.

3.6 Insulation Resistance. The minimum insulation resistance between primary, shield and core to the secondary windings shall be 10000 megohms with 1000 volts dc applied.

3.7 Corona Discharge. The transformer shall be immersed in a dielectric fluid and tested using a Biddle Corona tester or equivalent. The Test voltage is to be limited to 10000 volts RMS. Measure and record the corona inception and extinction voltage. Record a corona profile plot.

4.0 IDENTIFICATION. The transformer shall be marked in accordance with MIL-T-27 and MIL-STD-130. Marking shall include the following:

PART NUMBER:	26916-050-005194-001	
DATE CODE:	YYWW	(YY = YEAR, WW = WEEK)
SERIAL NUMBER:		

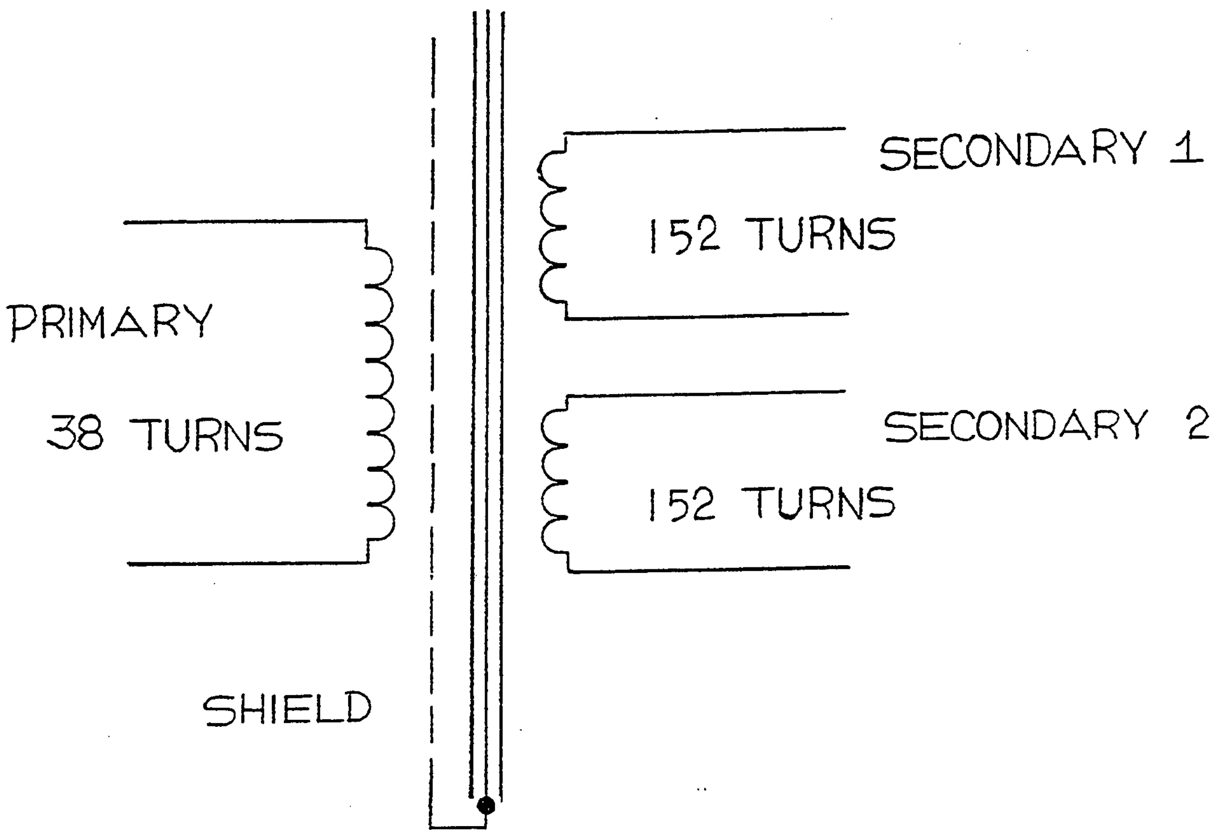


FIGURE 1. SCHEMATIC DIAGRAM

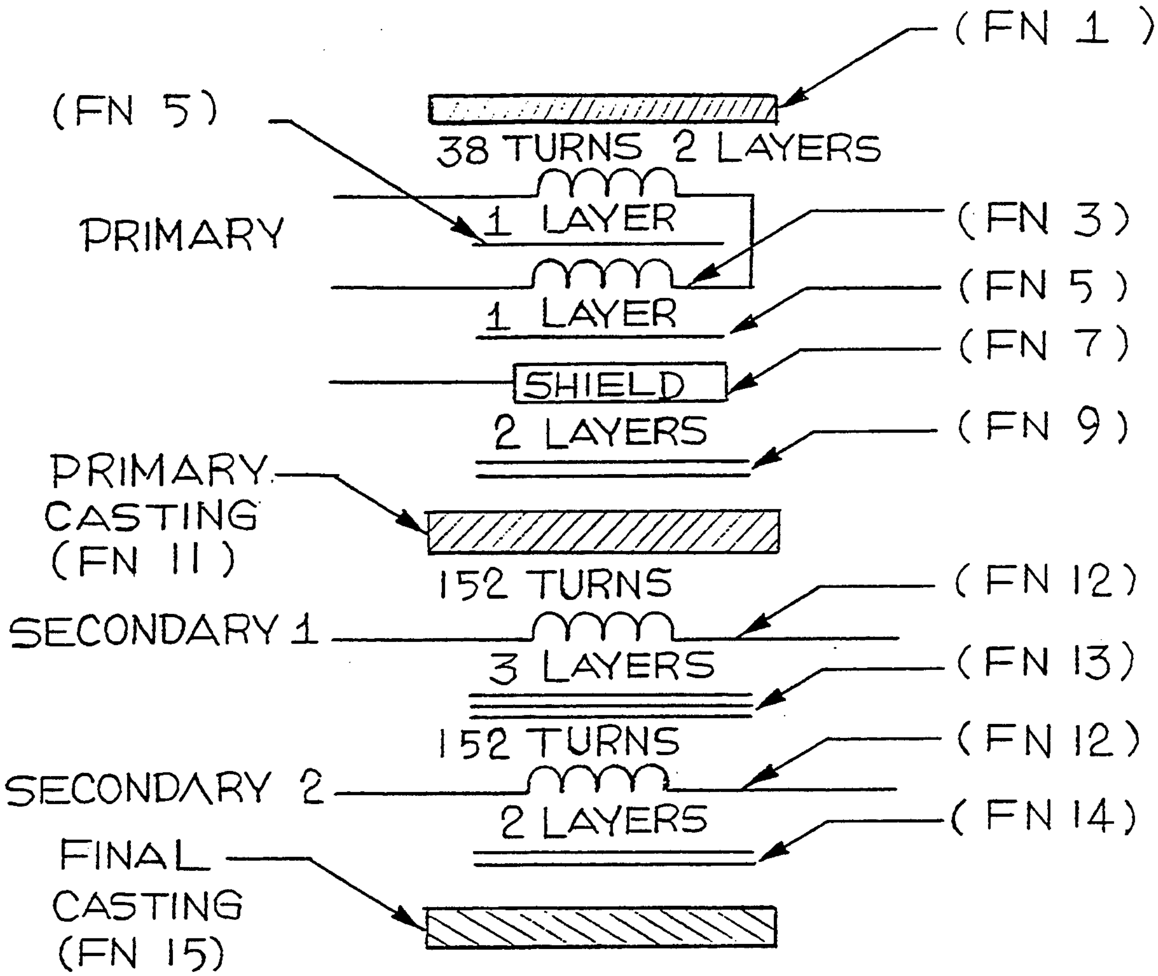


FIGURE 2. WINDING DIAGRAM

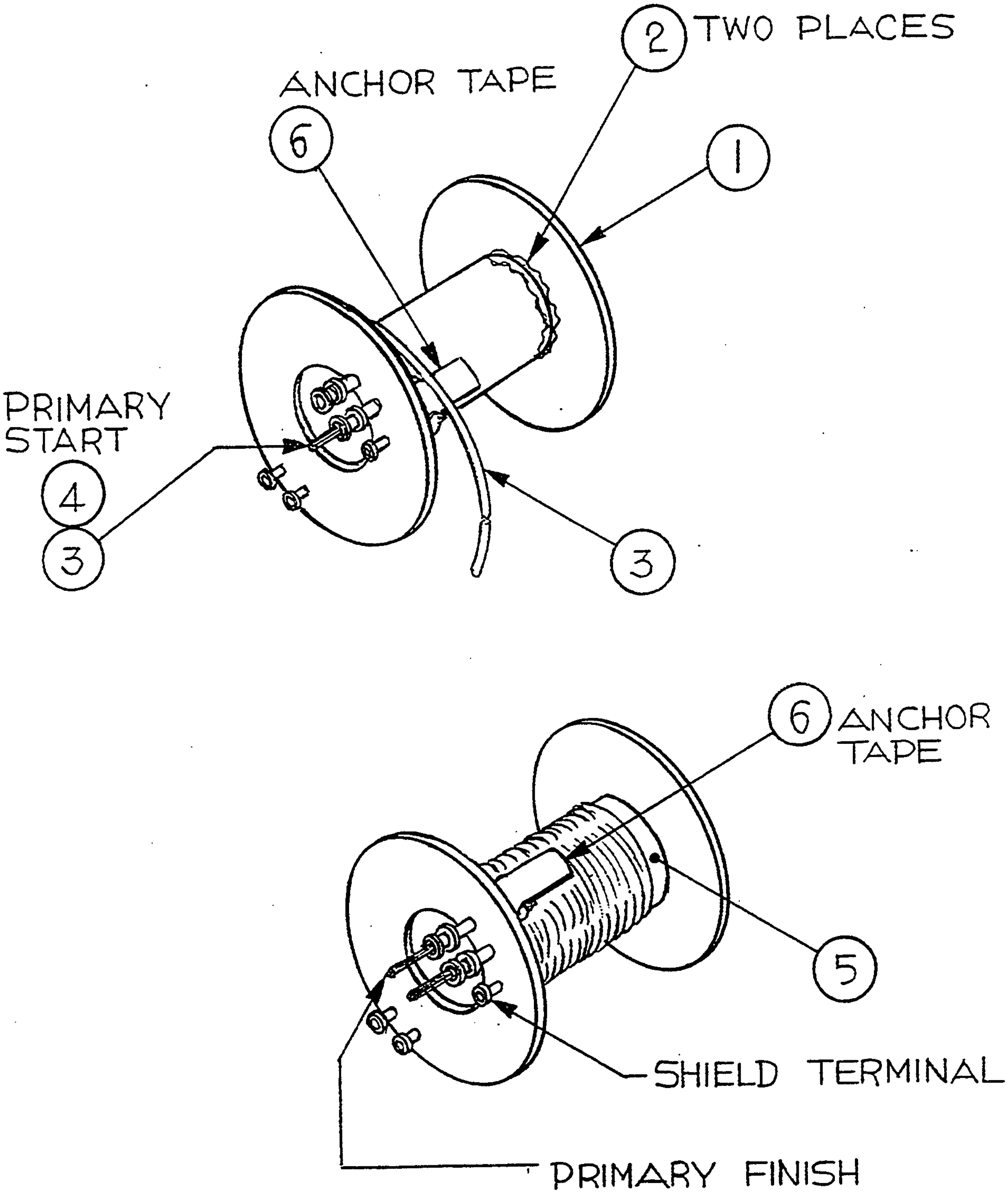


FIGURE 3. PRIMARY WINDING

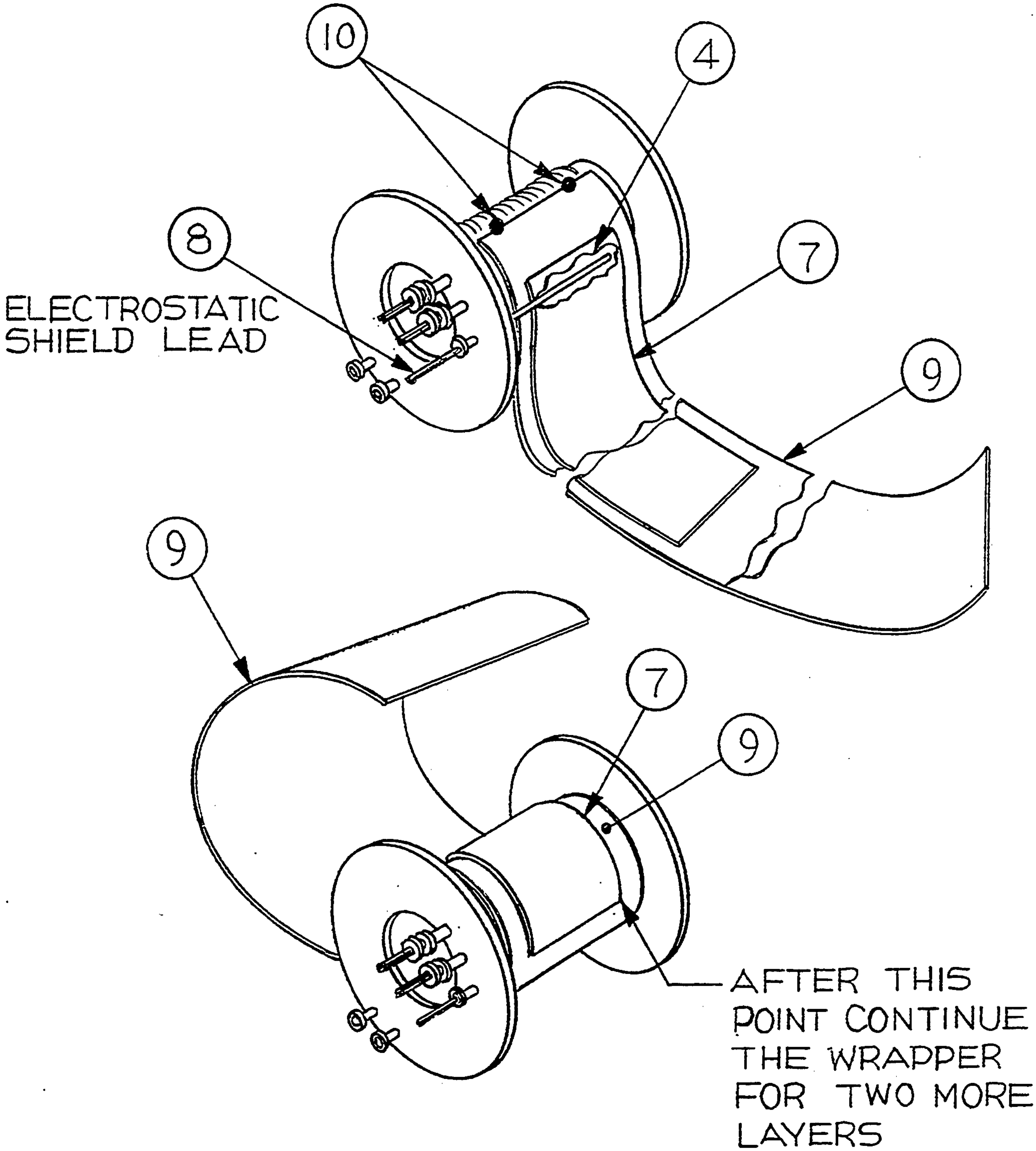


FIGURE 4. SHIELD

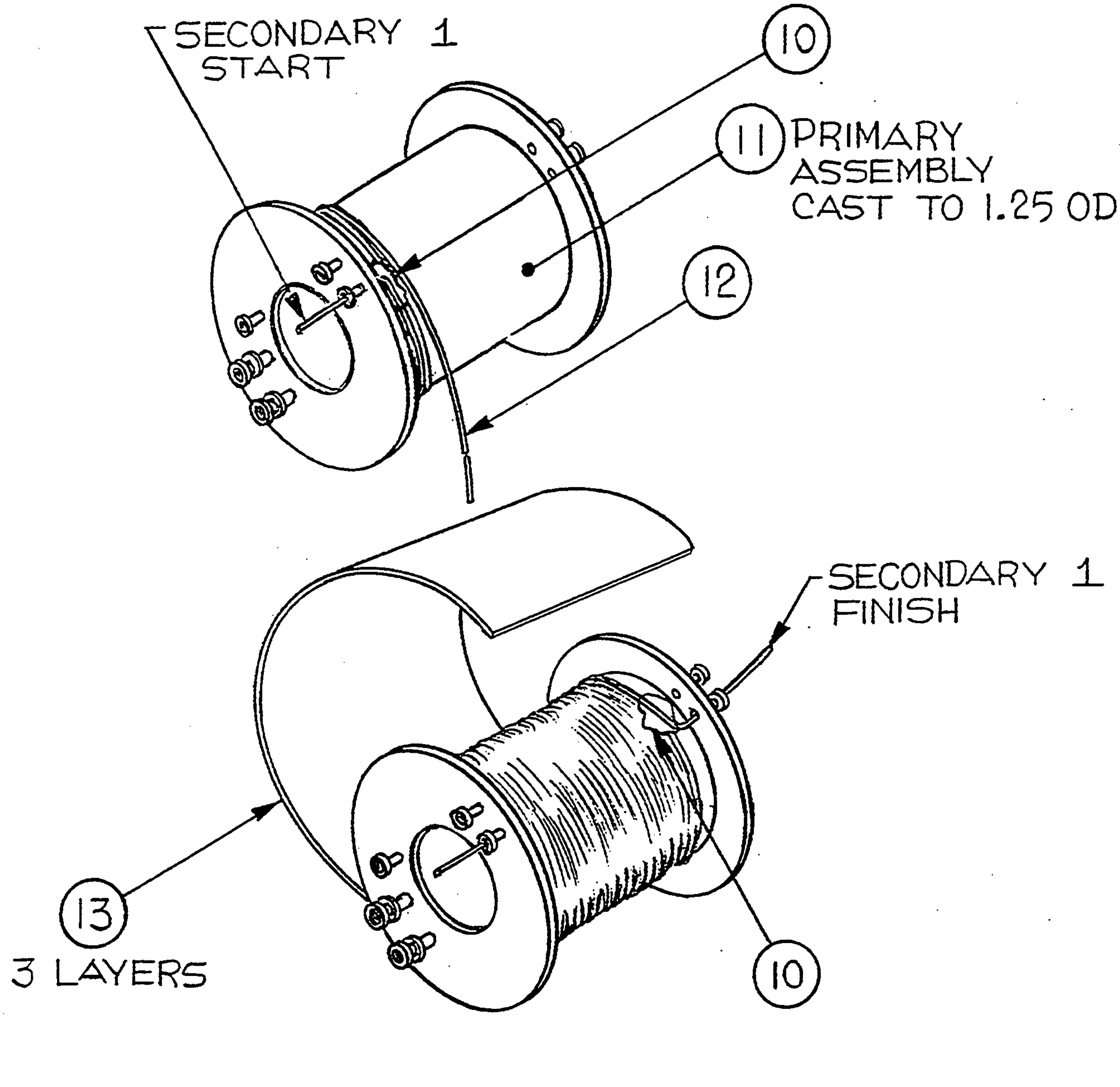


FIGURE 5. SECONDARY WINDING

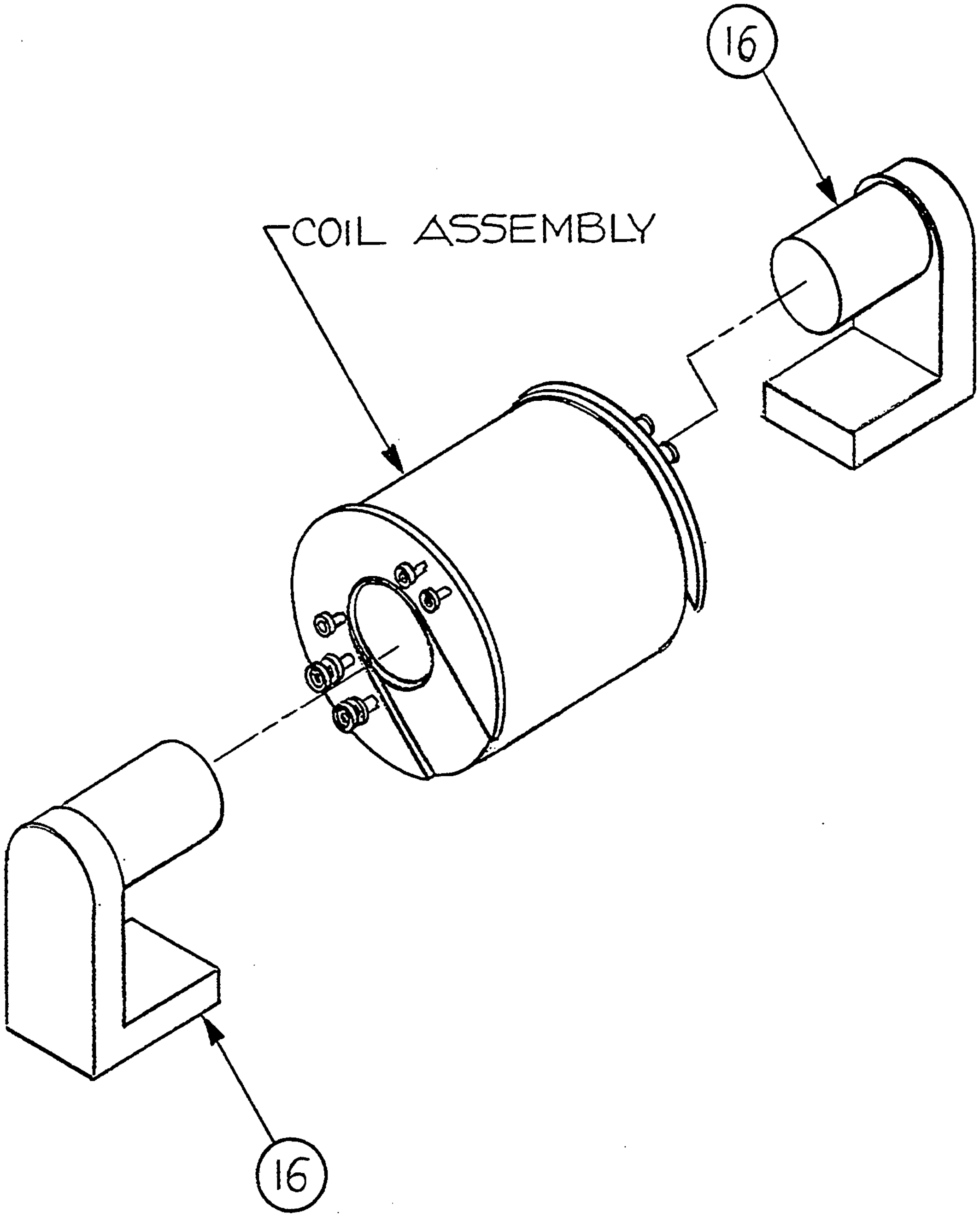


FIGURE 6. TRANSFORMER ASSEMBLY

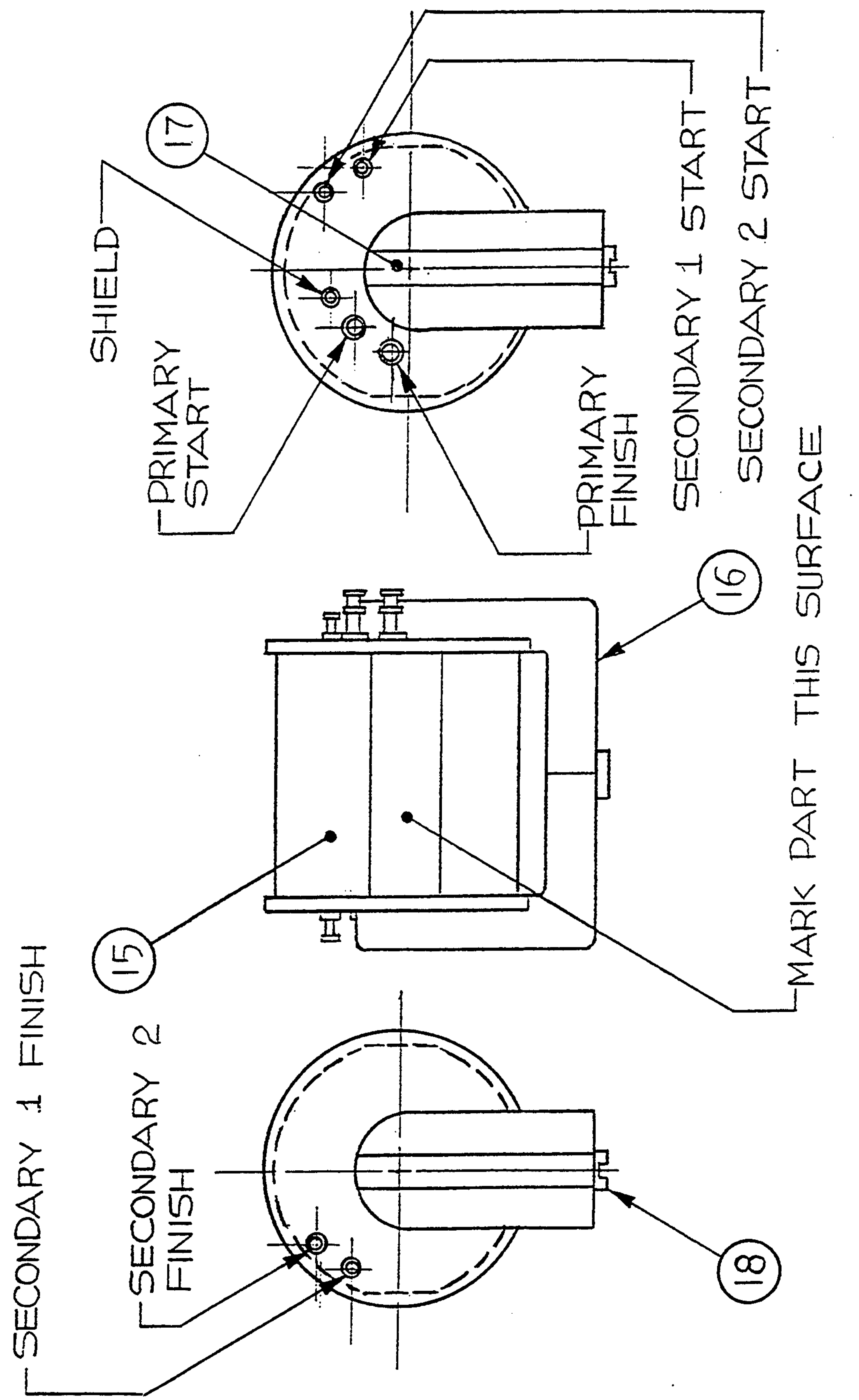


FIGURE 7. FINAL ASSEMBLY

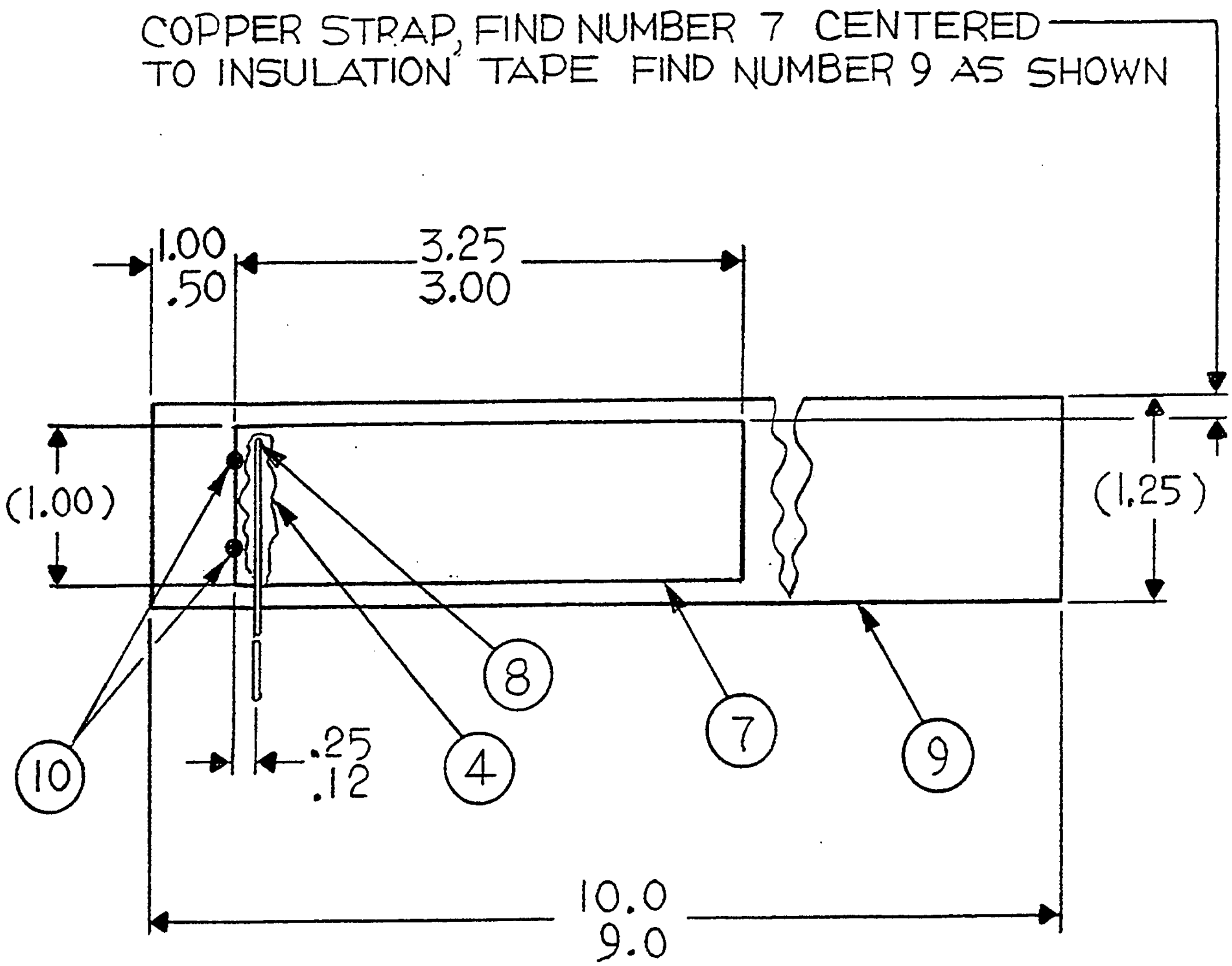


FIGURE 8. STRAP ASSEMBLY (SHIELD)

DESIGN AND MANUFACTURING GUIDELINES

FOR HIGH VOLTAGE POWER SUPPLIES

APPENDIX 4-1

PRIMARY TRANSFORMER TEST STRUCTURE

Section B. Test Transformer Specification

11. SCOPE

1.1 SCOPE. THIS SPECIFICATION COVERS THE DETAIL REQUIREMENTS FOR A 40 KILOHERTZ HIGH VOLTAGE STEP-UP POWER TEST TRANSFORMER THAT WILL BE USED IN A PROCEDURE TESTING PROGRAM. PRIMARY INPUT VOLTAGE DESIGN REQUIREMENTS ARE 200 VOLTS TRUE RMS 40 KILOHERTZ SQUARE WAVE.

1.2 CLASSIFICATION.

1.2.1 TYPE DESIGNATION. TF5V03ZZ

2. APPLICABLE DOCUMENTS

2.1 SPECIFICATION, STANDARDS, AND HANDBOOKS. UNLESS OTHERWISE SPECIFIED, THE FOLLOWING SPECIFICATIONS, STANDARDS, AND HANDBOOKS OF THE ISSUE LISTED IN THAT ISSUE OF THE DEPARTMENT OF DEFENSE INDEX OF SPECIFICATION AND STANDARDS (DODISS) SPECIFIED IN THE SOLICITATION, FORM A PART OF THIS SPECIFICATION TO THE EXTENT SPECIFIED HEREIN.

SPECIFICATIONS

FEDERAL

QQ-S-571 SOLDER, TIN ALLOY; TIN-LEAD ALLOY; AND LEAD ALLOY.

J-W-1177 WIRE, MAGNET, ELECTRICAL

MILITARY

MIL-T-27 TRANSFORMERS AND INDUCTOR, GENERAL SPECIFICATIONS FOR.

MIL-F-14256 FLUX, SOLDERING, LIQUID (ROSIN BASE).

MIL-I-19166 INSULATION TAPE, ELECTRICAL, HIGH-TEMPERATURE GLASS FIBER, PRESSURE SENSITIVE.

STANDARDS

MILITARY

MIL-STD-130 IDENTIFICATION MARKING OF US MILITARY PROPERTY

MIL-STD-202 TEST METHODS FOR ELECTRONIC AND ELECTRICAL COMPONENTS PARTS.

MIL-STD-445	STANDARD GENERAL REQUIREMENTS FOR ELECTRONIC EQUIPMENT.
MIL-STD-810	ENVIRONMENTAL, TEST METHODS AND ENGINEERING GUIDELINES.

3. REQUIREMENTS

3.1 GENERAL. THE TRANSFORMER SHALL MEET THE REQUIREMENTS OF MIL-T-27 AND AS SPECIFIED HEREIN. IN CASE OF CONFLICT, THIS DRAWING SHALL TAKE PRECEDENCE.

3.2 MATERIALS. THE MATERIALS SHALL BE AS SPECIFIED HEREIN. HOWEVER, WHEN A MATERIAL IS NOT SPECIFIED, A MATERIAL SHALL BE USED WHICH WILL ENABLE THE TRANSFORMER TO MEET THE PERFORMANCE REQUIREMENTS SPECIFIED HEREIN.

3.2.1 CORE. THE CORE SHALL BE SELECTED FOR THE TRANSFORMER TO MEET THE REQUIREMENTS SPECIFIED HEREIN.

3.2.1.1 CURIE TEMPERATURE. THE CORE SHALL HAVE A CURIE TEMPERATURE GREATER THAN +170 DEGREES C.

3.2.2 WIRE. THE MAGNET WIRE USED FOR THE SECONDARY CONSTRUCTION OF THIS TRANSFORMER SHALL MEET THE REQUIREMENTS OF J-W-1177, CLASS 200, TYPE K2. THE WIRE USED FOR THE PRIMARY CONSTRUCTION OF THIS TRANSFORMER SHALL MEET THE REQUIREMENTS OF J-W-1177, CLASS 155, TYPE L. FORMED INTO A LITZ WIRE.

3.2.3 FLAMMABLE MATERIALS. MATERIALS SHALL BE AS SPECIFIED IN MIL-T-27. MATERIALS USED IN THE CONSTRUCTION OF THIS TRANSFORMER SHALL BE NONFLAMMABLE AND NONEXPLOSIVE.

3.2.4 FUNGUS. ALL EXTERNAL MATERIALS SHALL BE NONNUTRIENT TO FUNGUS GROWTH OR SHALL BE SUITABLY TREATED TO RETARD FUNGUS GROWTH. THE MANUFACTURER SHALL CERTIFY THAT ALL EXTERNAL MATERIALS ARE FUNGUS RESISTANCE (SEE MIL-T-27) OR SHALL PERFORM THE TEST SPECIFIED IN 4.3.5. THERE SHALL BE NO EVIDENCE OF FUNGUS GROWTH ON THE EXTERNAL SURFACES.

3.2.5 CORROSIVE MATERIALS. MATERIALS SHALL BE AS SPECIFIED IN MIL-T-27. CORROSIVE MATERIALS USED IN ANY OF THE MANUFACTURING PROCESSES SHALL BE REMOVED OR NEUTRALIZED SO THAT NO CORROSION WILL RESULT FROM SUCH USE. INSOFAR AS PRACTICABLE, MATERIAL USED IN THE CONSTRUCTION OF THE TRANSFORMER MEETING THE REQUIREMENTS OF THIS SPECIFICATION SHALL BE NONCORROSIVE.

3.2.6 SOLDER AND SOLDER FLUX. SOLDER, WHEN USED, SHALL BE IN ACCORDANCE WITH QQ-S-571. SOLDERING FLUX SHALL BE IN ACCORDANCE WITH MIL-F-14256.

3.3 DESIGN, CONSTRUCTION AND PHYSICAL DIMENSIONS. DESIGN CONSTRUCTION AND PHYSICAL DIMENSIONS SHALL BE SPECIFIED IN FIGURE 1.

3.3.1 SCHEMATIC DIAGRAM. SCHEMATIC DIAGRAM SHALL BE AS SHOWN IN FIGURE 2.

3.3.2 DUTY CYCLE. THE TRANSFORMER SHALL BE DESIGNED FOR CONTINUOUS DUTY OPERATION.

3.3.3 CONSTRUCTION. THE TRANSFORMER SHALL BE CAST USING A SEMI-FLEXIBLE EPOXY RESIN. THE UNIT IS TO BE GRIT BLASTED EXCEPT FOR THE TERMINAL PINS. SEE FIGURE 1.

3.4 PERFORMANCE CHARACTERISTICS. THE TRANSFORMER SHALL PERFORM SATISFACTORILY WHEN SUBJECTED TO ANY AND ALL NATURAL COMBINATIONS OF TESTS SPECIFIED IN TABLE I. THERE SHALL BE NO BREAKAGE OR MALFUNCTIONS, OR EVIDENCE OF DAMAGE WHICH WOULD IMPAIR THE ABILITY OF THE TRANSFORMER TO MEET THE TEST REQUIREMENTS.

3.4.1 ELECTRICAL CHARACTERISTICS. THE TRANSFORMER SHALL MEET THE ELECTRICAL CHARACTERISTICS LISTED HEREIN WHEN TESTED AS SPECIFIED IN 4.3.2.

3.4.1.1 WINDING CONTINUITY. WHEN TESTED AS SPECIFIED IN 4.3.2.1, THE MAXIMUM DC PRIMARY RESISTANCE SHALL BE 60 MILLIOHMS. THE MAXIMUM DC RESISTANCE OF THE TWO SECONDARY WINDINGS CONNECT IN SERIES SHALL BE 28 OHMS.

3.4.1.2 ELECTRICAL RATING. (DESIGN INFORMATION) WHEN TESTED AS SPECIFIED IN 4.3.2.2, THE ELECTRICAL CHARACTERISTICS AT 40 KILOHERTZ SHALL BE WITHIN THE SPECIFIED VALUES AS FOLLOWS:

3.4.1.2.1 PRIMARY. 200 ± 1 VOLTS TRUE RMS, 40 KILOHERTZ SQUAREWAVE.

3.4.1.2.2 SECONDARY LOAD CURRENTS (WORST CASE). A CURRENT SOURCE SHALL BE APPLIED TO THE SECONDARY WINDINGS TO GENERATE A HEAT RISE OF UP TO 75 °C MAXIMUM.

3.4.1.3 NO-LOAD TURNS RATIO. WHEN TESTED AS SPECIFIED IN 4.3.2.3 THE NO-LOAD TURNS RATIO PRIMARY TO SECONDARIES SHALL BE WITHIN 2 PERCENT OF 1 : 4 : 4.

3.4.1.4 INDUCTANCE. WHEN THE TRANSFORMER IS TESTED AS SPECIFIED IN 4.3.2.4, THE INDUCTANCE OF THE PRIMARY WINDING SHALL BE GREATER THAN 3 MILLIHENRIES.

3.4.1.4.1 LEAKAGE INDUCTANCE. WHEN THE TRANSFORMER IS TESTED AS SPECIFIED IN 4.3.2.4, THE LEAKAGE INDUCTANCE MEASURED ACROSS THE PRIMARY WITH BOTH SECONDARIES SHORTED SHALL NOT EXCEED 30 MICRO-HENRIES.

3.4.1.5 POLARITY. WHEN THE TRANSFORMER IS TESTED AS SPECIFIED IN 4.3.2.5, THE RESULTS SHALL BE, THAT ALL THE SECONDARY WINDING TERMINALS EXITING THE SAME END OF THE COIL SHALL BE LIKE POLARITY.

3.4.1.6 ELECTROSTATIC SHIELD. WHEN THE ELECTROSTATIC SHIELD IS TESTED AS SPECIFIED IN 4.3.2.6, THE DETECTOR VOLTAGE SHALL BE RECORDED WITH THE SWITCH OPEN AND 100 VOLTS, 400 HERTZ APPLIED AS THE SOURCE. THE DETECTOR VOLTAGE IS THEN RECORDED WITH THE SWITCH CLOSED. THE RATIO OF THE OPEN SWITCH READING TO THE CLOSED SWITCH READING SHALL BE GREATER THEN 3.

3.4.1.7 INSULATION RESISTANCE. WHEN THE TRANSFORMER IS TESTED AS SPECIFIED IN 4.3.2.7, THE MINIMUM INSULATION RESISTANCE BETWEEN PRIMARY, SHIELD AND CORE TO ALL SECONDARIES CONNECTED IN SERIES SHALL BE 10000 MEGOHMS WITH A 1000 VOLT TEST VOLTAGE.

3.4.1.8 DIELECTRIC WITHSTANDING VOLTAGE. WHEN THE TRANSFORMER IS TESTED AS SPECIFIED IN 4.3.2.8, THERE SHALL BE NO EVIDENCE OF INSULATION BREAKDOWN. THE TRANSFORMER SHALL WITHSTAND 10000 VOLTS RMS SECONDARY TO PRIMARY, CORE AND SHIELD. 500 VOLTS RMS PRIMARY TO SHIELD AND CORE AND 500 VOLTS RMS SHIELD TO CORE.

3.4.2 ENVIRONMENTAL REQUIREMENTS.

3.4.2.1 OPERATING TEMPERATURE RANGE. AMBIENT TEMPERATURE AND SECONDARY WINDING CURRENT IS CONTROL FOR SECONDARY TEMPERATURE TO BE AT 125 °C, 150 °C AND 175 °C.

3.4.2.3 TERMINAL STRENGTH. WHEN TESTED AS SPECIFIED IN 4.3.3.1 THERE SHALL BE NO EVIDENCE OF LOOSENING OR RUPTURING OF THE LEADS OR TERMINALS.

3.4.2.4 RESISTANCE TO SOLDERING HEAT. WHEN TESTED AS SPECIFIED IN 4.3.3.2, THERE SHALL BE NO DAMAGE TO THE INSULATION OR LOOSENING OF THE TERMINALS.

3.4.2.5 SOLDERABILITY. WHEN TESTED AS SPECIFIED IN 4.3.3.3, THE TRANSFORMER SHALL MEET THE APPLICABLE CRITERIA FOR SOLDERABILITY.

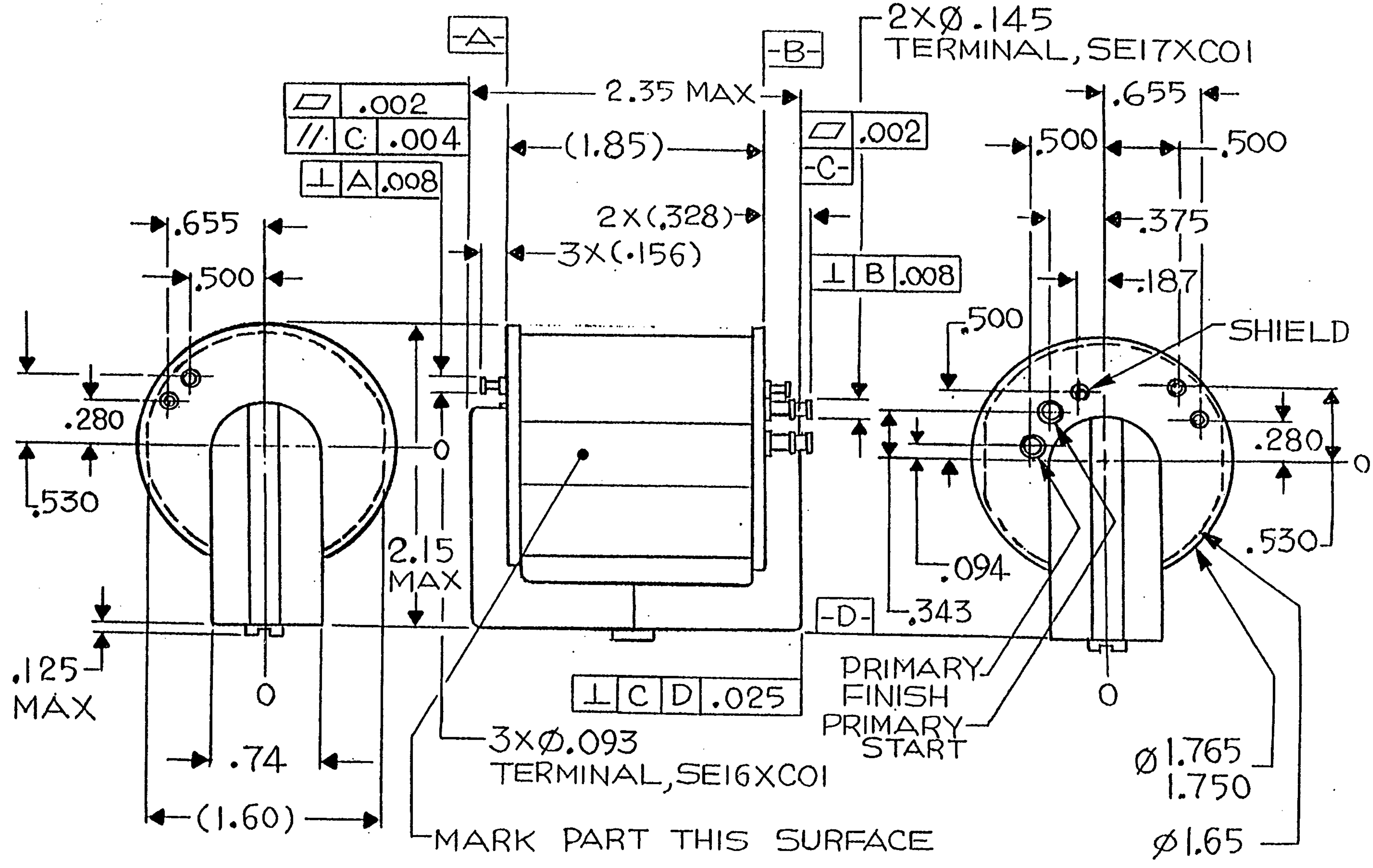


FIGURE 1. PHYSICAL DIMENSIONS

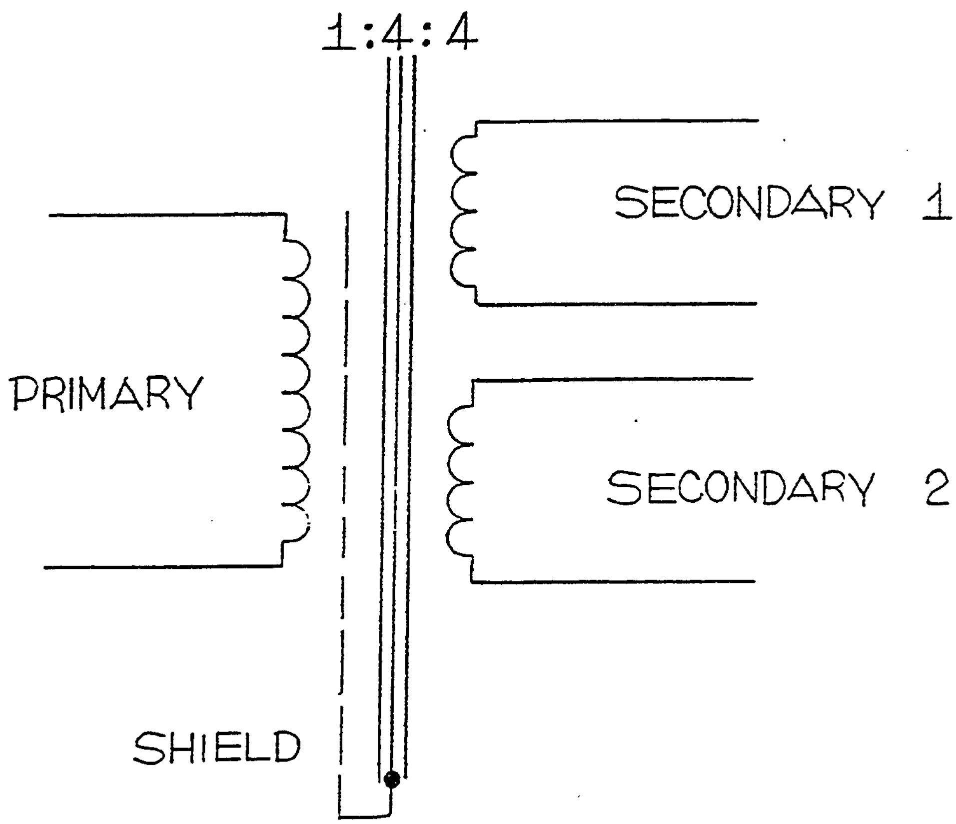


FIGURE 2. SCHEMATIC DIAGRAM

3.4.3 LIFE. WHEN TESTED AS SPECIFIED IN 4.3.4, THERE SHALL BE NO EVIDENCE OF PHYSICAL OR ELECTRICAL DAMAGE AS INDICATED BY AN OPEN OR SHORT CIRCUIT OR NOT BEING ABLE TO MEET THE INSULATION RESISTANCE OR DIELECTRIC WITHSTANDING VOLTAGE REQUIREMENTS.

3.5 WEIGHT. THE TRANSFORMER SHALL NOT EXCEED 9 OUNCES.

3.6 MARKING. THE TRANSFORMER SHALL BE MARKED IN ACCORDANCE WITH MIL-T-27 AND MIL-STD-130. MARKING SHALL INCLUDE THE FOLLOWING:

26916-50-005194

DATE CODE: YYWW (YY = YEAR, WW = WEEK)

SERIAL NUMBER:

3.6.1 TERMINAL IDENTIFICATION. TERMINAL AND LEADS SHALL BE IDENTIFIED BY POSITION AS SPECIFIED IN FIGURE 1.

3.7 WORKMANSHIP. WORKMANSHIP SHALL BE IN ACCORDANCE WITH MIL-T-27 AND THIS DRAWING, AND SHALL CONFORM TO MIL-STD-454, REQUIREMENT 9.

4. QUALITY ASSURANCE PROVISIONS

4.1 RESPONSIBILITY FOR INSPECTION. THIS IS A TEST TRANSFORMER TO TEST NORTHROP DSD PRODUCIBILITY TECHNIQUES.

4.2 MATERIAL INSPECTION. MATERIAL INSPECTION SHALL CONSIST OF CERTIFICATION THAT THE MATERIAL USED IN FABRICATION ON THIS PART ARE IN ACCORDANCE WITH 3.2.

4.3 METHODS OF EXAMINATION AND TEST.

4.3.1 VISUAL AND MECHANICAL EXAMINATION. THE TRANSFORMER SHALL BE EXAMINED TO VERIFY THAT THE MATERIALS, EXTERNAL DESIGN AND CONSTRUCTION, PHYSICAL DIMENSIONS, WEIGHT, MARKING, AND WORKMANSHIP ARE IN ACCORDANCE WITH APPLICABLE REQUIREMENTS (SEE 3.2, 3.3, 3.4, 3.5, 3.6, AND 3.7).

4.3.2 ELECTRICAL CHARACTERISTICS. THE ELECTRICAL CHARACTERISTICS SHALL BE DETERMINED BY THE TESTS SPECIFIED HEREIN, AS APPLICABLE (SEE 3.4.1).

4.3.2.1 WINDING CONTINUITY (SEE 3.4.1.1). ALL WINDINGS OF THE TRANSFORMER SHALL BE TESTED FOR ELECTRICAL CONTINUITY BY ANY MEANS. WHEN DC RESISTANCE IS TO BE MEASURED, KELVIN CONNECTIONS SHALL BE USED.

. 4.3.2.2 ELECTRICAL RATINGS (SEE 3.4.1.2). THE PRIMARY AND SECONDARY RATINGS SHALL BE DETERMINED BY ANY SUITABLE MEANS. (THIS IS DESIGN INFORMATION)

4.3.2.2.1 RATED LOAD (SEE 3.4.1.2.2). THE TRANSFORMER SHALL BE TESTED IN ACCORDANCE WITH MIL-T-27.

4.3.2.3 NO-LOAD TURNS RATIO (SEE 3.4.1.3). THE NO-LOAD TURNS RATIO SHALL BE TESTED IN ACCORDANCE WITH MIL-T-27.

4.3.2.4 INDUCTANCE (SEE 3.4.1.4). THE INDUCTANCE OF THE WINDING SHALL BE MEASURED AT 40 KILOHERTZ ON A WAYNE KERR PRECISION INDUCTANCE ANALYZER 3245, OR EQUIVALENT.

4.3.2.5 POLARITY (SEE PARA 3.4.1.5). THE POLARITY OF THE WINDINGS SHALL BE TESTED AS SPECIFIED IN MIL-T-27.

4.3.2.6 ELECTROSTATIC SHIELD (SEE PARA 3.4.1.6). THE ELECTROSTATIC SHIELD SHALL BE TESTED AS SPECIFIED IN MIL-T-27 UNLESS OTHERWISE SPECIFIED.

4.3.2.7 INSULATION RESISTANCE (SEE 3.4.1.7). THE INSULATION RESISTANCE SHALL BE TESTED AS SPECIFIED IN MIL-T-27.

4.3.2.8 DIELECTRIC WITHSTAND VOLTAGE (SEE 3.5.1.8). THE DIELECTRIC WITHSTANDING VOLTAGE SHALL BE TESTED AS SPECIFIED IN MIL-T-27.

4.3.3 ENVIRONMENTAL REQUIREMENTS. THE ENVIRONMENTAL REQUIREMENTS SHALL BE DETERMINED AS SPECIFIED HEREIN.

4.3.3.1 TERMINAL AND LEAD STRENGTH (SEE 3.4.2.3). THE TRANSFORMER SHALL BE TESTED FOR TERMINAL STRENGTH IN ACCORDANCE WITH MIL-T-27 USING THE SOLID-WIRE AND INSULATED LEAD WIRE METHOD.

4.3.3.2 RESISTANCE TO SOLDER HEAT (SEE 3.4.2.4). THE TRANSFORMER SHALL BE TESTED IN ACCORDANCE WITH MIL-T-27 USING EITHER THE SOLDER BATH OR SOLDERING IRON METHOD.

4.3.3.3 SOLDERABILITY (SEE 3.4.2.5). THE TRANSFORMER SHALL BE TESTED IN ACCORDANCE WITH MIL-STD-202, METHOD 208.

4.3.4 LIFE (SEE 3.4.3). THE TRANSFORMER SHALL BE TESTED IN ACCORDANCE WITH MIL-T-27.

4.3.5 FUNGUS (SEE 3.2.4). UNLESS CERTIFICATION IS PROVIDED, THE TRANSFORMER SHALL BE TESTED IN ACCORDANCE WITH METHOD 508 OF MIL-STD-810.

TABLE I QUALITY CONFORMANCE 100 PERCENT TESTING

EXAMINATION OF TEST	REQUIREMENT PARAGRAPH	METHOD PARAGRAPH
VISUAL AND MECHANICAL EXAMINATION (EXTERNAL)	3.2, 3.3, 3.4, 3.5, 3.6 AND 3.7	4.3.1
WINDING CONTINUITY	3.4.1.1	4.3.2.1
NO-LOAD TURNS RATIO	3.4.1.3	4.3.2.3
INDUCTANCE	3.4.1.4 AND 3.4.1.4.1	4.3.2.4
POLARITY	3.4.1.5	4.3.2.5
ELECTROSTATIC SHIELD	3.4.1.6	4.3.2.6
INSULATION RESISTANCE	3.4.1.7	4.3.2.7
DIELECTRIC WITHSTANDING VOLTAGE	3.4.1.8	4.3.2.8

5.NOTES

5.1 APPROVED SOURCE(S) OF SUPPLY:

NORTHROP DSD PART NUMBER	MANUFACTURER	MANUFACTURER PART NUMBER	CAGE CODE
050-005194-001	NORTHROP CORP DEFENSE SYSTEMS DIVISION ROLLING MEADOWS, ILLINOIS	050-005194-001	26916

DESIGN AND MANUFACTURING GUIDELINES

FOR HIGH VOLTAGE POWER SUPPLIES

APPENDIX 4-2

MODIFIED TRANSFORMER TEST STRUCTURE

1. SCOPE

1.1 SCOPE. THIS SPECIFICATION COVERS THE DETAIL REQUIREMENTS FOR A TEST VEHICLE TO BE USED IN A DESIGN EXPERIMENT TO TEST METHODS OF WINDING TERMINATIONS IN HIGH VOLTAGE TRANSFORMERS. THE PURPOSE OF THIS DESIGN EXPERIMENT IS TO TEST THE RELIABILITY OF TWO METHODS OF STRIPPING MAGNET WIRE. THESE TEST WIRES WILL BE SIMULATING THE NATURAL LEADS OF A TRANSFORMER WINDING BETWEEN THE WINDING ANCHOR AND THE TERMINATION. EACH WIRE END WILL HAVE A STRESS RELIEF BEND. THE WIRES UNDER TEST WILL BE EMBEDDED IN A FILLED SEMI-FLEXIBLE CLASS F EPOXY RESIN, SCOTCHCAST 281, DURING FINAL CASTING. IN THIS DESIGN EXPERIMENT, 16 SETS OF WIRES WILL BE STRESS TESTED ON EACH TEST ASSEMBLY WHILE BEING THERMAL CYCLED. THE METHODS OF STRIPPING THE WIRE WILL BE; SCRAPPING AND TINNING AND BY STRIPPING THE WIRE IN A SOLDER POT.

1.2 CLASSIFICATION.

1.2.1 TYPE DESIGNATION. THIS TEST VEHICLE IS TO BE MANUFACTURED USING THE SAME PROCEDURES AS WOULD BE USED IN ASSEMBLING A MIL-T-27, GRADE 5, CLASS V POWER TRANSFORMER, LESS CORE.

2. APPLICABLE DOCUMENTS

2.1 SPECIFICATION, STANDARDS, AND HANDBOOKS. UNLESS OTHERWISE SPECIFIED, THE FOLLOWING SPECIFICATIONS, STANDARDS, AND HANDBOOKS OF THE ISSUE LISTED IN THAT ISSUE OF THE DEPARTMENT OF DEFENSE INDEX OF SPECIFICATION AND STANDARDS (DODISS) SPECIFIED IN THE SOLICITATION, FORM A PART OF THIS SPECIFICATION TO THE EXTENT SPECIFIED HEREIN.

SPECIFICATIONS

FEDERAL

J-W-1177	WIRE, MAGNET, ELECTRICAL
QQ-S-571	SOLDER, TIN ALLOY; TIN-LEAD ALLOY; AND LEAD ALLOY.

MILITARY

MIL-T-27	TRANSFORMERS AND INDUCTOR, GENERAL SPECIFICATIONS FOR.
MIL-F-14256	FLUX, SOLDERING, LIQUID (ROSIN BASE).
MIL-I-16923	INSULATION COMPOUND, ELECTRICAL, EMBEDDING, EPOXY.

MIL-I-19166	INSULATION TAPE, ELECTRICAL, HIGH-TEMPERATURE GLASS FIBER, PRESSURE SENSITIVE.

STANDARDS

MILITARY

MIL-STD-130	IDENTIFICATION MARKING OF US MILITARY PROPERTY
MIL-STD-202	TEST METHODS FOR ELECTRONIC AND ELECTRICAL COMPONENT PARTS.
MIL-STD-454	STANDARD GENERAL REQUIREMENTS FOR ELECTRONIC EQUIPMENT.
MIL-STD-810	ENVIRONMENTAL, TEST METHODS AND ENGINEERING GUIDELINES.

3. REQUIREMENTS

3.1 GENERAL. THE SIMULATED TRANSFORMER CONFIGURATION SHALL MEET THE REQUIREMENTS OF A MIL-T-27 TYPE COMPONENT AND AS SPECIFIED HEREIN. IN CASE OF CONFLICT, THIS DRAWING SHALL TAKE PRECEDENCE.

3.2 MATERIALS. THE MATERIALS SHALL BE AS SPECIFIED HEREIN. HOWEVER, WHEN A MATERIAL IS NOT SPECIFIED, A MATERIAL SHALL BE USED WHICH WILL ENABLE THE TEST COIL TO MEET THE PERFORMANCE REQUIREMENTS SPECIFIED HEREIN.

3.2.1 WIRE. THE MAGNET WIRES USED TO SIMULATE THE TRANSFORMER SECONDARIES SHALL BE AWG 34 AND SHALL MEET THE REQUIREMENTS OF J-W-1177, CLASS 200, TYPE K2 OR CLASS 130, TYPE UV, AS SPECIFIED. THE WIRE USED FOR THE PRIMARY CONSTRUCTION OF THIS COIL SHALL MEET THE REQUIREMENTS OF J-W-1177, CLASS 155, TYPE L. FORMED INTO A 100 X 38 LITZ WIRE.

3.2.2 FLAMMABLE MATERIALS. MATERIALS SHALL BE AS SPECIFIED IN MIL-T-27. MATERIALS USED IN THE CONSTRUCTION OF THIS SIMULATED TRANSFORMER COIL ASSEMBLY SHALL BE NONFLAMMABLE AND NONEXPLOSIVE.

3.2.3 SOLDER AND SOLDER FLUX. SOLDER, WHEN USED, SHALL BE IN ACCORDANCE WITH QQ-S-571. SOLDERING FLUX SHALL BE IN ACCORDANCE WITH MIL-F-14256.

3.3 DESIGN, CONSTRUCTION AND PHYSICAL DIMENSIONS. DESIGN CONSTRUCTION AND PHYSICAL DIMENSIONS SHALL BE SPECIFIED ON FIGURES 1, 2, 3 AND TABLE I.

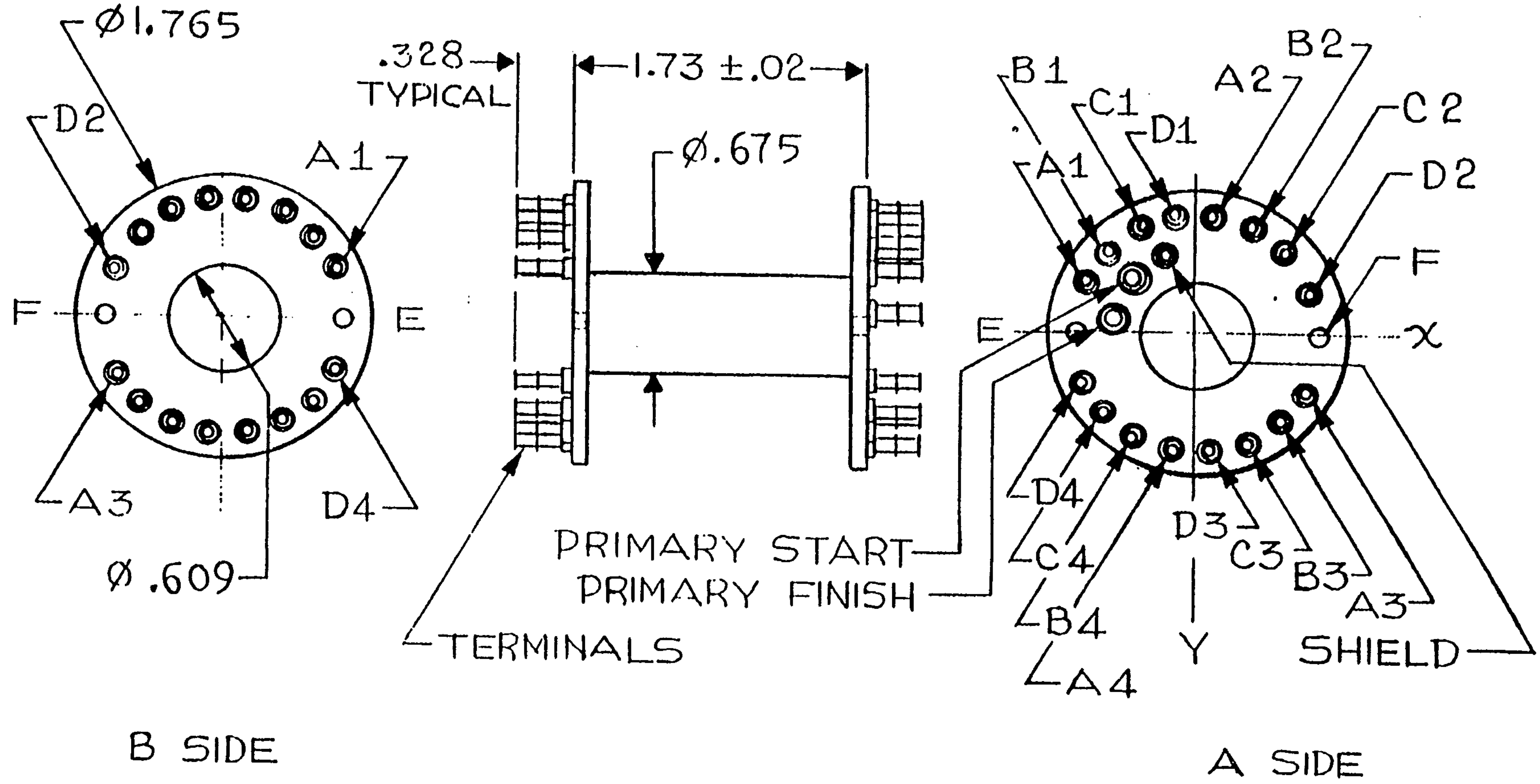


FIGURE 1. COIL FORM CONFIGURATION SEE TABLE I FOR TERMINAL LOCATIONS.

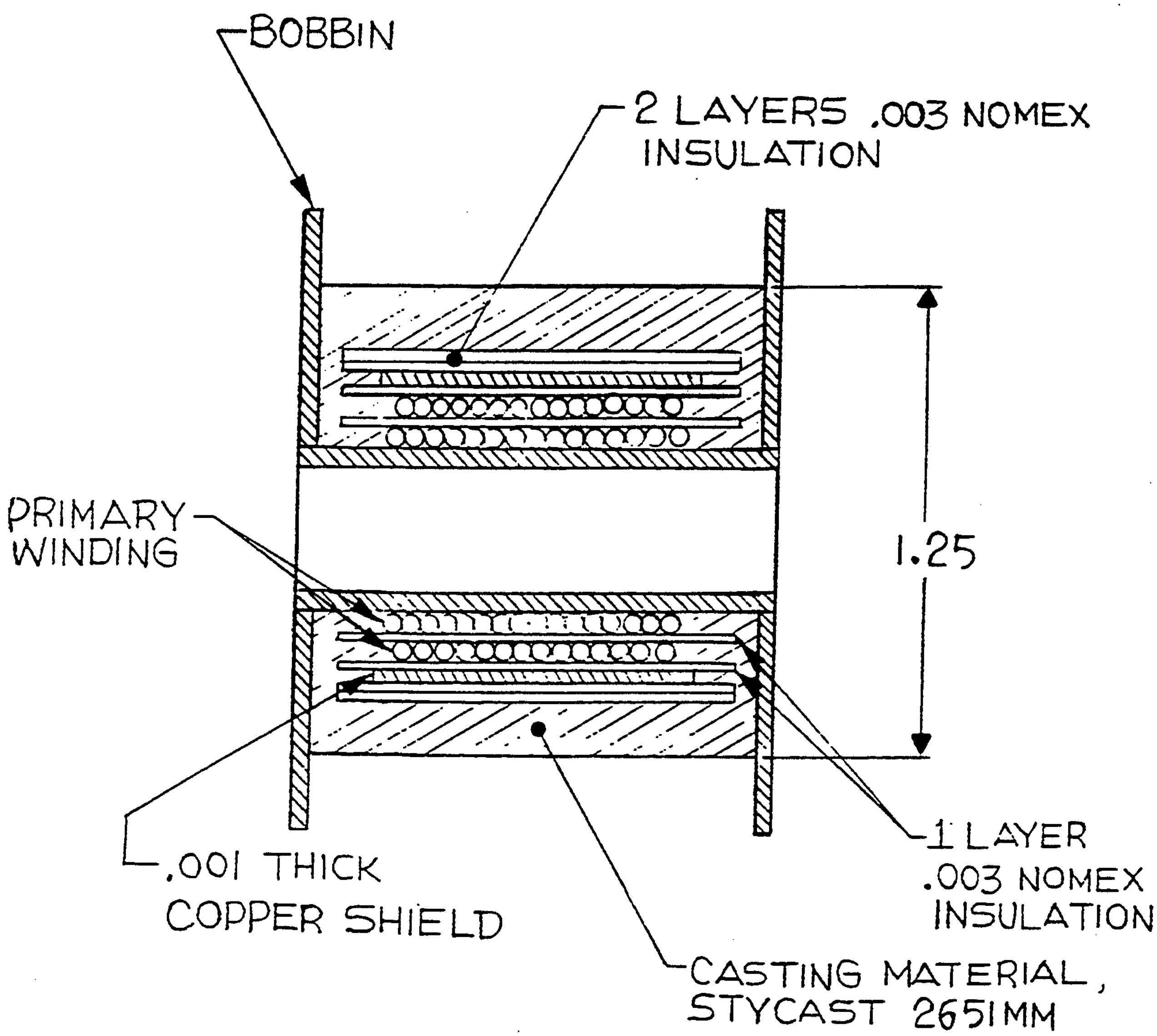
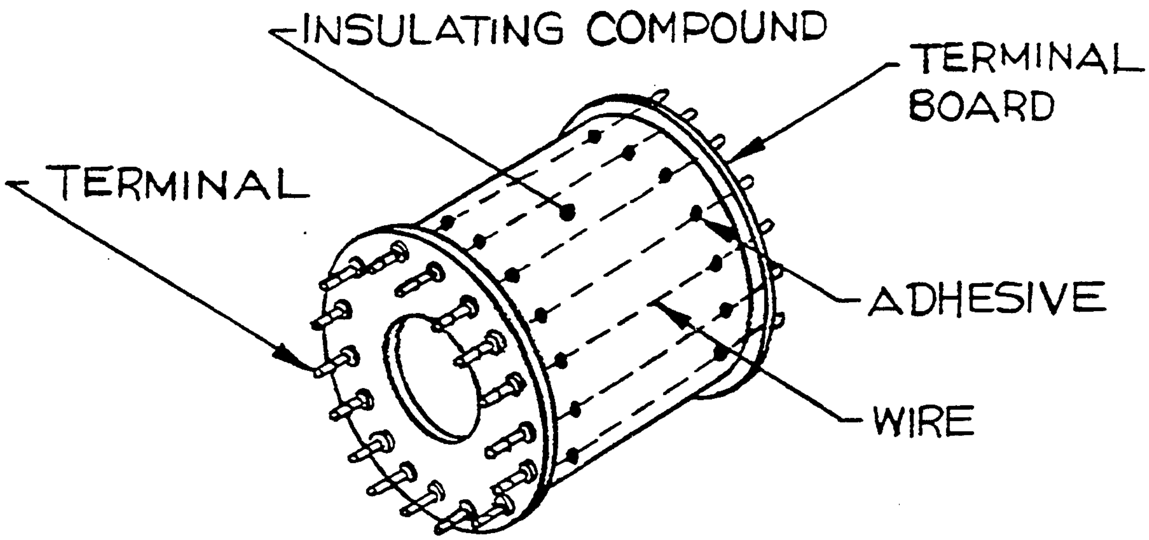
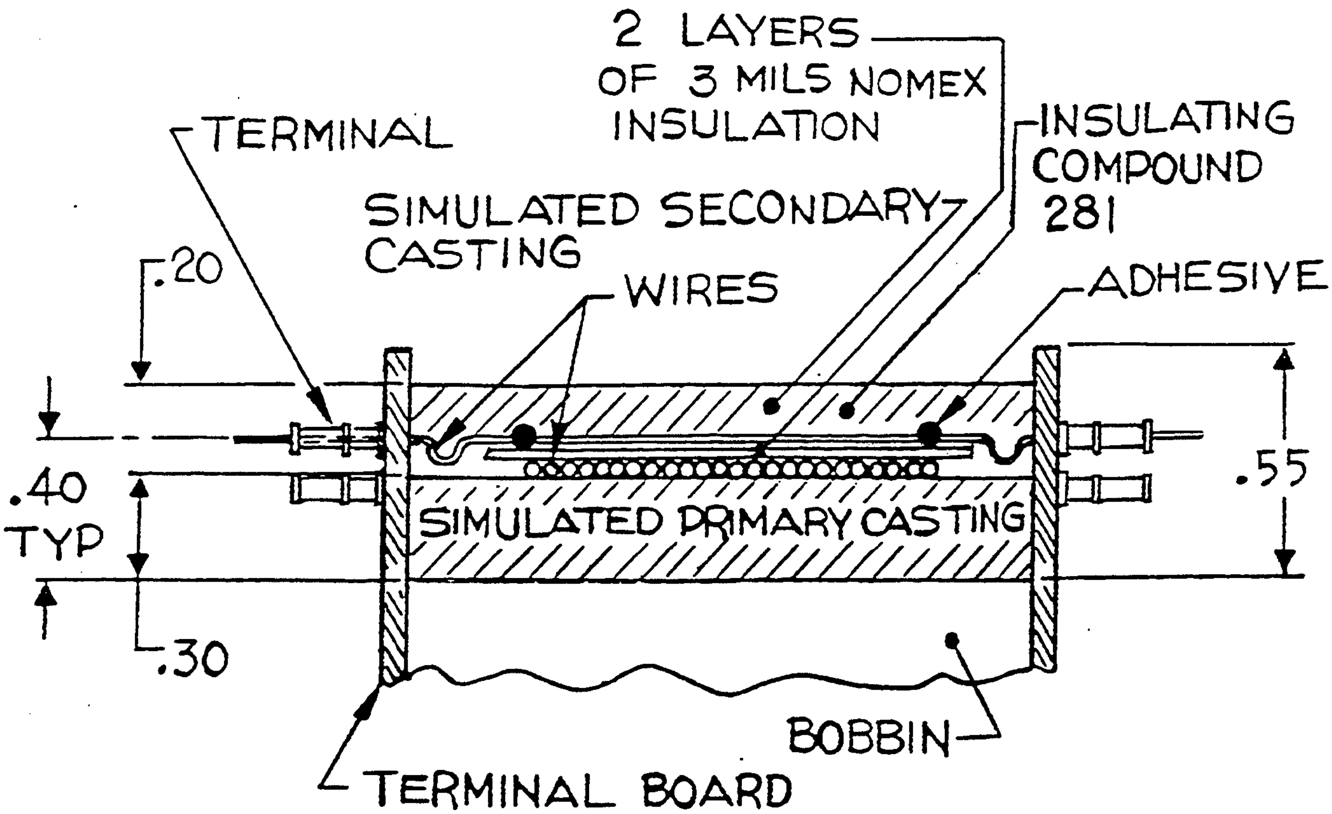


FIGURE 2. CAST PRIMARY - TERMINALS NOT SHOWN FOR CLARITY



TEST FIXTURE



SECTION VIEW

FIGURE 3. CAST SECONDARY

TABLE I. DIMENSIONS FOR PIN LOCATION (INCHES)

PIN IDENTIFICATION	X (A SIDE)	X (B SIDE)	Y
A1	-.659	.659	.312
B1	-.530	.530	.500
C1	-.350	.350	.639
D1	-.135	.135	.716
A2	.093	-.093	.716
B2	.312	-.312	.659
C2	.500	-.500	.530
D2	.655	-.655	.312
A3	.639	-.639	-.350
B3	.500	-.500	-.530
C3	.312	-.312	-.659
D3	.093	-.093	-.716
A4	-.135	.135	-.716
B4	-.350	.350	-.639
C4	-.530	.530	-.500
D4	-.659	.659	-.312
PRIMARY START	-.375	----	.343
PRIMARY FINISH	-.500	----	.094
SHIELD	-.187	----	.500
E (THRU HOLE)	-.718	.718	0
F (THRU HOLE)	.718	-.718	0

3.3.1 SCHEMATIC DIAGRAM. SCHEMATIC DIAGRAM SHALL BE AS SHOWN ON FIGURE 4.

3.3.2 DUTY CYCLE. THE TRANSFORMER COIL SHALL BE DESIGNED FOR CONTINUOUS DUTY OPERATION.

3.3.3 CONSTRUCTION. THE TRANSFORMER COIL SHALL BE CAST IN TWO STAGES. THE PRIMARY AND SHIELD SECTION IS TO BE CAST WITH A LOW THERMAL COEFFICIENT OF EXPANSION GENERAL PURPOSE EPOXY CASTING RESIN AND MEET THE DIMENSIONS AS SPECIFIED ON FIGURE 2. THE FINAL OVERCASTING IS TO BE A FILLED SEMI-FLEXIBLE CLASS F EPOXY RESIN AND MEET THE DIMENSIONAL REQUIREMENTS AS SPECIFIED ON FIGURE 3.

3.4 PERFORMANCE CHARACTERISTICS. THE SIMULATED TRANSFORMER COIL SHALL PERFORM SATISFACTORILY WHEN SUBJECTED TO ANY AND ALL NATURAL COMBINATIONS OF TESTS SPECIFIED. AN OPEN IS CONSIDERED A FAILURE.

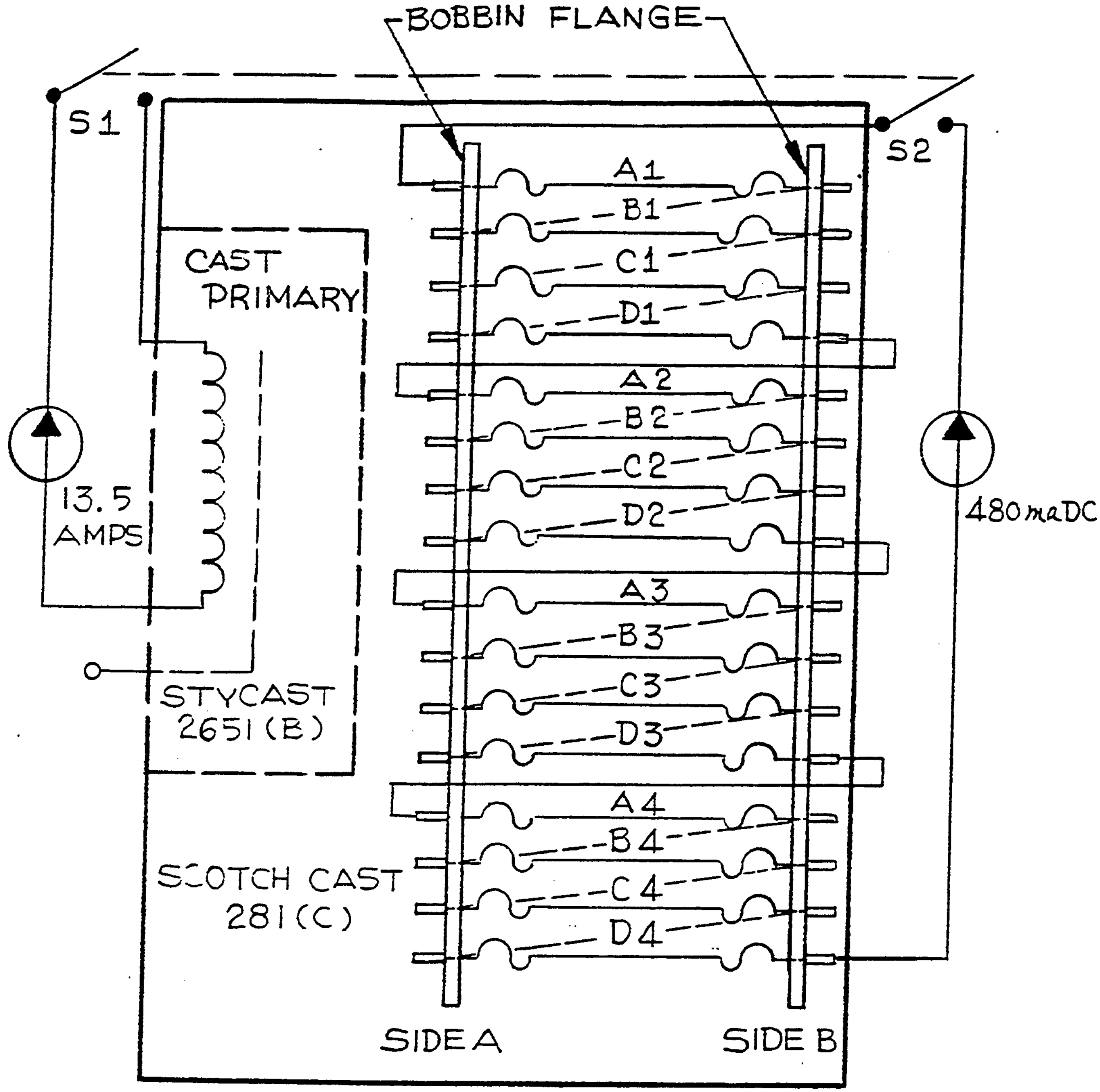
3.4.1 ELECTRICAL CHARACTERISTICS. THE SIMULATED TRANSFORMER COIL SHALL MEET THE ELECTRICAL CHARACTERISTICS LISTED HEREIN AND TESTED AS SPECIFIED IN 4.2.2.

3.4.1.1 WINDING CONTINUITY. WHEN TESTED AS SPECIFIED IN 4.2.2.1, THE MAXIMUM DC PRIMARY RESISTANCE SHALL BE 60 MILLIOHMS.

3.4.1.2 ELECTRICAL DESIGN INFORMATION.

3.4.1.2.1 PRIMARY. THE TRANSFORMER COIL ASSEMBLY, FOR THIS DESIGN TEST, IS TO BE CONSTRUCTED IN TWO LEVELS. THE FIRST LEVEL WILL BE THE PRIMARY WINDING AND SHIELD ASSEMBLY, SEE FIGURES 1 AND 2 . ON A FULLY ASSEMBLED AND GRIT BLASTED COIL FORM WIND ON, IN TWO LEVEL LAYERS, 38 TURNS OF 100X36 LITZ WIRE. A SLIGHTLY OVERLAPPING SINGLE LAYER OF .003 INCH THICK 418 NOMEX INSULATION CUT TO WIDTH IS TO BE USED FOR LAYER INSULATION. THE WINDING IS TO BE TWO 19 TURN LAYERS CENTERED ON THE COIL FORM LEAVING EQUAL MARGINS ON BOTH ENDS. THE PRIMARY WINDING IS TO BE WRAPPED WITH ONE LAYER OF .003 INCH THICK 418 NOMEX FOLLOWED WITH A .001 INCH THICK COPPER SHIELD. A FINAL WRAPPER OF TWO LAYERS OF .003 INCH THICK 418 NOMAX IS TO BE WRAPPED ON THE COIL ASSEMBLY BEFORE IT IS CASTED IN A MOLD TO THE DIMENSION SPECIFIED ON FIGURE 2. UV CURED ADHESIVE IS TO BE USED TO HOLD THE INSULATION AND SHIELD IN PLACE. AT THIS STAGE THE ASSEMBLY IS PLACED IN A MOLD AND CAST USING A LOW THERMAL COEFFICIENT OF EXPANSION GENERAL PURPOSE EPOXY CASTING RESIN, STYCAST 2651MM. THE CURED CAST ASSEMBLY IS TO BE GRIT BLASTED AND CLEANED TO REMOVE ALL TRACES OF FLASHING AND FOREIGN MATERIALS.

3.4.1.2.2 SIMULATED SECONDARIES. ON A CAST PRIMARY ASSEMBLY, WIND ON A SINGLE LAYER SOLENOID WINDING OF 152 TIGHTLY WOUND TURNS OF K2 AWG 34 MAGNET WIRE. THIS WINDING IS TO BE CENTERED ON THE COIL ASSEMBLY WITH BOTH ENDS ANCHORED TO THE PRIMARY ASSEMBLY USING UV ADHESIVES. THE LEADS FOR THIS WINDING DO NOT EXIT THE COIL. THIS



"A" AND "C" PIN WIRES ARE SOLDER STRIPPED, CLASS 130, TYPE UV, MAGNET WIRE.

"B" AND "D" PIN WIRES ARE SCRAPPED AND SOLDER TINNED, CLASS 200, TYPE K2, MAGNET WIRE.

FIGURE 4. SCHEMATIC DIAGRAM AND TEST CIRCUIT

4.2.9

WINDING IS USED TO SIMULATE A WINDING AND THERMAL PATH. WRAP THE COIL WITH TWO LAYERS OF .003 THICK 418 NOMEX INSULATION. FIGURE 4 DESCRIBES WHICH TYPE OF WIRE AND STRIPPING IS CONNECTED TO EACH SET OF TERMINALS. 32 WIRE CONNECTIONS WILL BE TESTED ON EACH ASSEMBLY. EACH WIRE WILL BE ANCHORED IN PLACE WITH UV ADHESIVE AND HAVE A STRESS RELIEF BEND AS SHOWN ON FIGURE 3.

3.4.2 ENVIRONMENTAL REQUIREMENTS.

3.4.2.1 OPERATING TEMPERATURE RANGE. THE COMPLETED ASSEMBLY IS TO BE CONTINUALLY THERMAL CYCLED IN A CHAMBER THAT'S AMBIENT TEMPERATURE IS VARIED IN AN EIGHT HOUR CYCLE OF -55 °C TO +100 °C. DURING THE LAST HOUR OF +100 °C THE SWITCHES SHOWN ON FIGURE 4 ARE CLOSED. WITH THE CURRENTS SPECIFIED THE TEMPERATURE OF THE AREA AROUND THE JUNCTIONS UNDER TEST WILL RISE TO 150 °C. SEE FIGURE 5.

3.5 MARKING. THE TRANSFORMER SHALL BE MARKED IN ACCORDANCE WITH MIL-T-27 AND MIL-STD-130. MARKING SHALL INCLUDE THE FOLLOWING:

26916-50-005193

DATE CODE: YYWW (YY = YEAR, WW = WEEK)

SERIAL NUMBER:

3.5.1 TERMINAL IDENTIFICATION. TERMINALS AND LEADS SHALL BE IDENTIFIED BY POSITION AS SPECIFIED ON FIGURE 1.

3.6 WORKMANSHIP. WORKMANSHIP SHALL BE IN ACCORDANCE WITH MIL-T-27 AND THIS DRAWING, AND SHALL CONFORM TO MIL-STD-454, REQUIREMENT 9.

4. QUALITY ASSURANCE PROVISIONS

4.1 MATERIAL INSPECTION. MATERIAL INSPECTION SHALL CONSIST OF CERTIFICATION THAT THE MATERIAL USED IN FABRICATION ON THIS PART ARE IN ACCORDANCE WITH 3.2.

4.2 METHODS OF EXAMINATION AND TEST. (SEE TABLE II)

4.2.1 VISUAL AND MECHANICAL EXAMINATION. THE SIMULATED TRANSFORMER SHALL BE EXAMINED TO VERIFY THAT THE MATERIALS, EXTERNAL DESIGN AND CONSTRUCTION, PHYSICAL DIMENSIONS, WEIGHT, MARKING, AND WORKMANSHIP ARE IN ACCORDANCE WITH APPLICABLE REQUIREMENTS (SEE 3.2, 3.3, 3.4, 3.5, AND 3.6).

4.2.2 ELECTRICAL CHARACTERISTICS. THE ELECTRICAL CHARACTERISTICS SHALL BE DETERMINED BY THE TESTS SPECIFIED HEREIN, AS APPLICABLE (SEE 3.4.1).

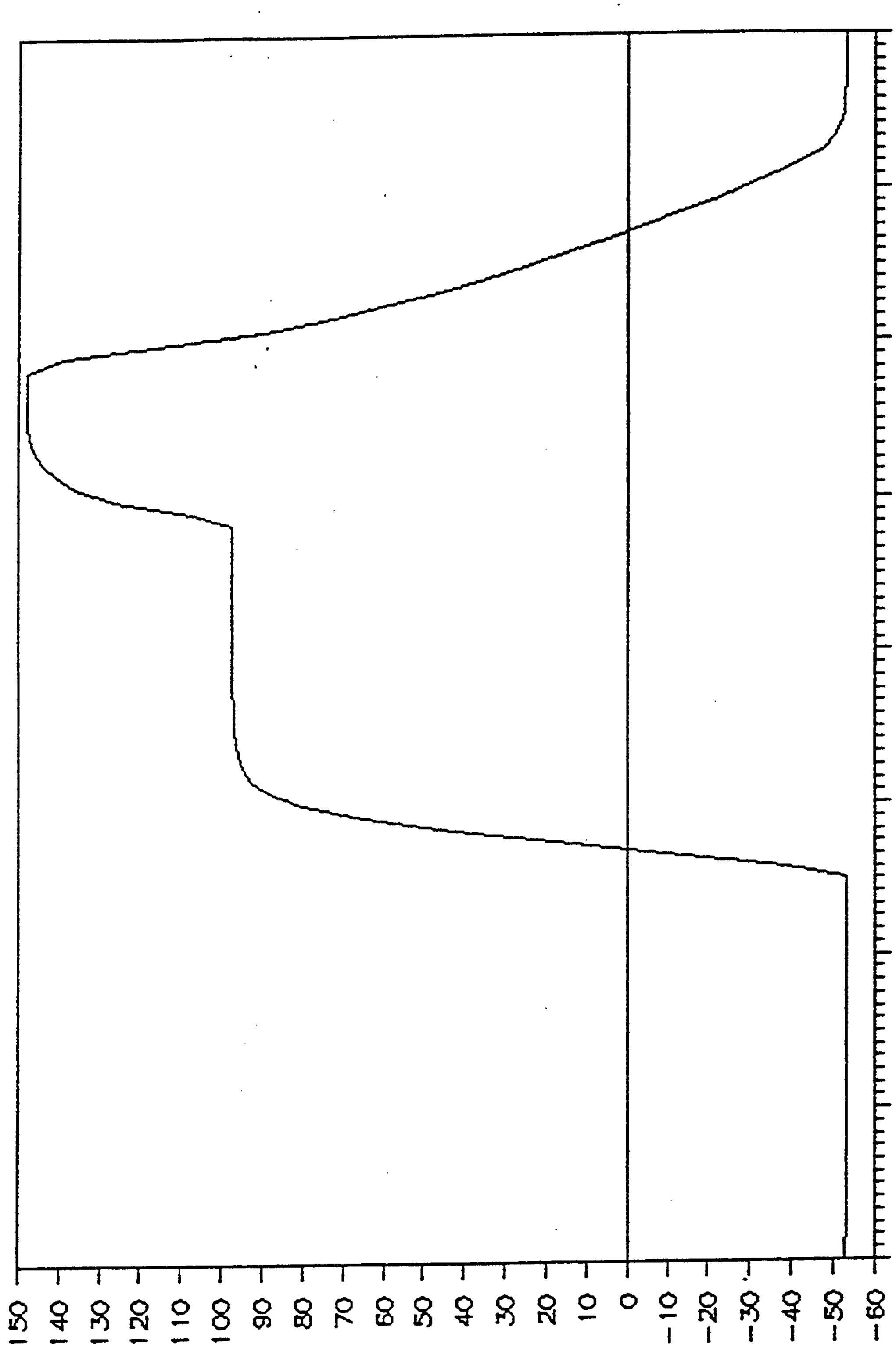


FIGURE 5. TEMPERATURE CYCLING

4.2.2.1 <u>WINDING CONTINUITY (SEE 3.4.1.1)</u>. THE PRIMARY WINDING AND THE TEST WIRES SHALL BE TESTED FOR ELECTRICAL CONTINUITY BY ANY MEANS. WHEN DC RESISTANCE IS TO BE MEASURED, KELVIN CONNECTIONS SHALL BE USED.

4.2.3 <u>ENVIRONMENTAL REQUIREMENTS</u>. THE ENVIRONMENTAL REQUIREMENTS SHALL BE DETERMINED AS SPECIFIED HEREIN.

TABLE II QUALITY CONFORMANCE 100 PERCENT TESTING

EXAMINATION OF TEST	REQUIREMENT PARAGRAPH	METHOD PARAGRAPH
VISUAL AND MECHANICAL EXAMINATION (EXTERNAL)	3.2, 3.3, 3.4, 3.5, AND 3.6	4.2.1
WINDING CONTINUITY	3.4.1.1	4.2.2.1

5.NOTES

5.1 APPROVED SOURCE(S) OF SUPPLY:

NORTHROP DSD PART NUMBER	MANUFACTURER	MANUFACTURER PART NUMBER	CAGE CODE
050-005193-001	NORTHROP CORP ELECTRONICS SYSTEMS DIVISION ROLLING MEADOWS ILLIONIS	050-005193-001	26916